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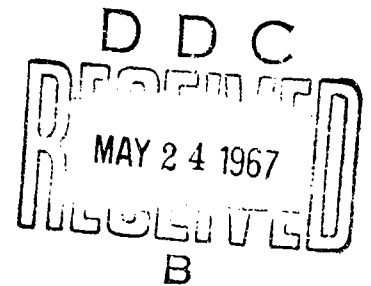# USAAVLABS TECHNICAL REPORT 67-8

AN INVESTIGATION OF THE THRUST AUGMENTATION CHARACTERISTICS OF JET EJECTORS

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DEPARTMENT OF THE ARMY
U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS. VIRGINIA 23604

This report has been reviewed by the US Army Aviation Materiel
Laboratories and is considered to be technically sound.

The work was performed under Contract DA 44-177-AMC-322(T) in
order to determine the capabilities and limitations of the jet
ejector as a thrust augmentor. As a result of this program a
rapid method for jet ejector performance prediction was
formulated and is herein offered as a tool for the designer.

AN INVESTIGATION OF THE THRUST AUGMENTATION CHARACTERISTICS OF JET EJECTORS

by

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Prepared by

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FORT EUSTIS, VIRGINIA

SUMMARY

Presented in this investigation is a theoretical analysis of
the thrust augmentation characteristics of jet ejectors.
The analysis includes the effects of flow compressibility,
major flow losses, and forward speed. Numerical results are
presented in the form of nomographs for a wide range of
practical operating conditions. These computations were
performed with the aid of an IBM 360 digital computer. The
charts can be used to predict the jet ejector performance
and as such represent an effective analytical tool for
preliminary design purposes. The numerical results are used
to determine the effects of the more important aerodynamic,
thermodynamic, and geometric parameters on jet ejector
thrust augmentation. A correlation of these results with the
available experimental data is also made.

FOREWORD

This report presents analyses and numerical evaluations of
the thrust augmentation characteristics of jet ejectors.
The work was sponsored by the U. S. Army Aviation Materiel
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performed by the Dynasciences Corporation, Blue Bell,
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Mr. Roy Burrows was the Army technical representative. His
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SYMBOLS

A	cross-sectional area, square feet
a	radius of the primary jet, feet
C_c	compressibility correction factor ϕ_c/ϕ_I
c_p	specific heat at constant pressure, British thermal units per pound per degree Rankine
D	diameter of the mixing chamber, feet
d	diameter of the nozzle, feet
F	thrust, pounds
f	friction factor
g	acceleration of gravity, 32.17 feet per second squared
H	total head, pounds per square foot
h	correction for ρ_{Ip} in the Newton-Raphson iterative procedure
i	an index number
J	mechanical equivalent of heat, 778.2 foot-pounds per British thermal unit
K_I, K_2	programmed constants for the initial conditions in the iteration procedure
k	correction for V_2 in the Newton-Raphson iterative procedure
L	length of the mixing chamber, feet
M	Mach number

m	mass flow rate, pounds per second
N	number of nozzles
P	pressure, pounds per square foot
R	gas constant, British thermal units per pound per degree Rankine
r	jet boundary distance from the jet axis, feet
r'	radial distance from jet center line nondimensionalized by the jet radius
S	contact area, square feet
T	temperature, degrees Rankine
V	velocity, feet per second
V_α	forward speed of the jet ejector system parallel to the ejector axis, feet per second
w	entrainment ratio (mass flow ratio)
X	distance from the jet exit along the ejector-axis, feet
α_E	secondary-to-primary area ratio
α_D	diffuser exit-to-entrance area ratio
γ	specific heat ratio
ϵ	iteration convergence criteria
η	thermal efficiency factor
η_M	mixing efficiency
θ	primary jet expansion angle, degrees

κ a parameter defining nonuniform velocity profile at the secondary entrance

λ_D diffuser loss factor defined as

$$\lambda_D = \frac{H_2 - H_3}{\dfrac{\rho V_2^2}{2g}\left(1 - \dfrac{1}{\alpha_D}\right)^2}$$

λ_E secondary entrance loss factor defined as

$$\lambda_E = \frac{H_a - H_{1_S}}{\dfrac{\rho V_{1_S}^2}{2g}}$$

μ ratio of the forward speed to the velocity of the jet exhausted directly to the ambient

ξ an integral defined by equation (110)

ρ density, pounds per cubic foot

ϕ thrust augmentation ratio

χ empirical correction factor for thrust augmentation ratio due to nonuniform velocity profile at the secondary entrance

ψ_1, ψ_2 denote equations (154) and (155) , respectively

SUBSCRIPTS

A   annular

a   denotes the ambient conditions

c   compressibility

D   diffuser

E   entrance

I   ideal

L   losses

M   multiple

o   denotes the stagnation conditions

p   pertains to the primary flow

s   single

s   pertains to the secondary flow

1   denotes Station 1, i.e., the plane at the exit
           of the primary nozzle, which is also the plane
           at the entrance to the mixing chamber

2   denotes Station 2, i.e., the plane at the exit
           of the mixing chamber, which is also the plane
           at the entrance to the diffuser

3   denotes Station 3, i.e., the plane at the exit
           of the diffuser

NOTE: Symbols with bars denote uniform values in the
           one-dimensional idealized analysis.

I. INTRODUCTION

The concept of generating thrust augmentation by means of a
jet ejector became an active research subject several
decades ago. Since then, numerous studies have been
conducted providing a considerable amount of jet ejector
data. Much of this work was done, however, for different
and diverse applications, and because of the complexity of
the jet ejector flow problems, the available information
cannot be readily used for practical applications to aircraft
design and performance.

The main objective of this program is to evaluate the avail-
able data as to their practical applicability and to extend
and modify existing theories to provide an analysis for
realistic appraisal of the potential of jet ejectors for
achieving augmented thrust.

The review of the existing literature covered a major
portion of technical reports (total 585) which are listed
in Appendix II. A discussion of the more important of these
investigations is presented in Section III.

The theoretical analyses which are formulated in Section IV
are performed for an axisymmetric ejector and include the
effects of compressibility, flow losses, and ejector geom-
etry. These analyses utilize various simplifying assumptions,
among which are the conditions that the velocity profile at
the secondary entrance is uniform and that the mixing of the
primary and secondary flows is completed at the exit of the
mixing chamber. The former assumption limits the appli-
cability of this one-dimensional theoretical approach to
not too large secondary-to-primary area ratios. A three-
dimensional analysis is indeed a formidable task and has not
been undertaken by any of the investigators in the past. To
keep the complexity of the analysis within the scope of the
present program, an empirical correction factor for thrust
augmentation ratio is herein formulated to account for the
effect of the nonuniform velocity distribution at the
secondary entrance. The latter assumption implies that the
mixing chamber length of a given ejector configuration must
be sufficiently long to ensure complete mixing of the exit
flows. No precise information is available on this subject,
and therefore a semiempirical approach is herein utilized

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for qualitative evaluation of the mixing chamber length
required for complete mixing.

Furthermore, a comprehensive parametric study is conducted
to determine the effects of the more important aerodynamic,
thermodynamic, and geometric parameters on jet ejector
performance. A discussion of these effects is presented in
Section V.

Section VI contains a correlation of the theoretical results
with the available experimental data.

Section VII contains a summary of the theoretical results
for rapid predictions of jet ejector performance. These
results were obtained with the aid of an IBM 360 digital
computer and are presented as nomographs.

II. JET EJECTOR PRINCIPLE

A jet ejector is a device in which a secondary, or driven,
fluid is entrained by a primary or actuating fluid with
subsequent transfer of energy through turbulent mixing in a
mixing chamber. The primary fluid, which is originally at a
higher stagnation pressure, is discharged with a high
velocity into the mixing chamber of specific shape. Due to
viscous shear, the fluid surrounding the primary flow is
brought into motion at the entrance of the mixing chamber.
This motion causes a drop of static pressure, as a result of
which the secondary fluid, in many cases ambient air, is
entrained into the mixing chamber. The secondary flow thus
formed mixes turbulently with the primary jet in the mixing
chamber and energy transfer occurs. The mixed flow then
proceeds toward the exit end of the mixing chamber and
finally discharges to some back pressure which may be
atmospheric. If a diffuser is attached, the mixed flow
builds up some static pressure before reaching the exit. As
a result of the pumping action as described above, the total
momentum of the mixed flow at the ejector exit is increased
due to the entrainment of the secondary fluid, as compared
with the momentum of the primary jet discharged directly into
the atmosphere. Jet thrust augmentation is thus achieved.

In essence, the jet ejector can be considered as a device
which converts a low mass flow propelled at high velocity to
a high mass flow propelled at low velocity. If this is
accomplished at little energy loss, thrust augmentation can
be achieved.

The efficiency of this conversion process depends on the
ejector configuration, the detail geometry of these configu-
rations, and the thermodynamic and aerodynamic operating
conditions.

The more important jet ejector configurations are as follows:

(a) Single nozzle ejector

(b) Multiple nozzle ejector

(c) Annular nozzle ejector

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The prime parameter affecting the performance of these configurations is the minimum mixing chamber length required for complete mixing of the primary and the secondary flows. No precise analytical methods are available for determining this parameter; therefore, a semiempirical method is herein formulated for this purpose. An analysis of various ejector types is presented in Section IV.

The major geometric parameters affecting thrust augmentation are:

(a) Secondary-to-primary area ratio at the entrance to the mixing chamber.

(b) Shape and length of the mixing chamber.

(c) Diffuser exit-to-entrance area ratio and diffuser angle.

(d) Primary nozzle configuration and location.

(e) Secondary entrance inlet contour.

Finally, the thermodynamic and aerodynamic parameters of importance are:

(a) Stagnation properties of the primary fluid.

(b) Stagnation properties of the secondary fluid.

(c) Atmospheric conditions at the ejector exit.

(d) Forward speed of the ejector system.

III.   REVIEW OF THE AVAILABLE PERTINENT LITERATURE

Presented in this section is a brief review of the state of
the art of jet ejectors. The papers selected for this
discussion are those which are more directly related to the
work under the present program, and they are herein arranged
in a chronological order. A more complete bibliography on
jet ejectors is presented in Appendix II.

The analysis performed by Roy (Reference 1) deals with
compressible fluid flow under practical operating conditions
of jet ejectors. Entrance and diffuser losses are accounted
for by assuming the flow processes as polytropic. The
friction loss at the mixing chamber wall is also considered.
This analysis results in a system of 24 flow equations for
which no close-form or digital computer solutions are
presented.

Morrisson (Reference 2) performs an incompressible analysis
in which it is assumed that the mass flow rate of the
primary jet exhausted to the ambient is the same as that
discharged into the mixing chamber. This assumption may not
be valid since the pressure reduction created in the mixing
chamber results in an increase of mass flow rate of the
primary jet as compared to that when the primary jet is
discharged into the atmosphere. The analysis presents
charts of thrust augmentation ratio versus the mass flow
ratio. However, these charts cannot readily be applied for
determining jet ejector performance, since the mass flow
rate is unknown.

Sargent (References 3 and 4) performs idealized analyses of
the performance of jet ejectors for both static and forward
speed conditions. In these analyses, the flows are assumed
to be incompressible and the solution for the flow equations
is made by a trial and error method with the area ratio and
mass flow ratio as variables. These analyses rely on the
assumption that the mass flow rate of the primary jet
exhausted to the ambient is equal to that of the primary jet
inside the ejector.

The analysis of McClintock et al (Reference 5) results in an
equation for thrust augmentation as a function of the mass
flow ratio which is not determined. In spite of the fact

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that the analysis is performed for incompressible fluids, an attempt is made to account for different densities of primary and secondary flows. This appears to be contradictory, since an incompressible analysis is only valid for primary and secondary fluids of nearly equal densities.

Ellerbrock's analysis (Reference 6), which includes the loss due to wall friction, treats compressible flow for constant area mixing. However, in obtaining solutions to the flow equations, assumed values of the pressure ratio at the ejector entrance plane to that of the ambient are introduced.

The analysis performed by von Kármán (Reference 7) presents the basic information on cylindrical jet ejectors operating under idealized, incompressible flow conditions. The expression for the nondimensionalized velocity of the mixed flow at the exit appears to be erroneous, although the relationship for thrust augmentation ratio finally obtained is correct. In this analysis, an attempt is made to account for the effect of the nonuniform velocity profile at the secondary entrance on jet ejector thrust augmentation. However, the analysis utilizes the assumption that the mass flow rate for the nonuniform velocity profile is the same as that in the case of uniform velocity distribution. As the result of this assumption, an increase rather than a reduction in thrust augmentation is achieved.

Szczeniowski, in his incompressible analysis (Reference 8), considers a hypothetical approach in which momentum and energy are transferred between the primary and secondary streams while the two flows remain separate at the exit of the ejector. The justification of this approach is rather difficult.

Sanders et al (Reference 9) compute the ejector thrust by integration of surface pressures; however, the momentum of the flow from the exit of the ejector is completely ignored. This approach does not yield the total thrust augmentation.

The analysis performed by Bertin et al (Reference 10) utilizes the usual one-dimensional flow approach but yields no close-form solution for the jet ejector performance. The

performance charts presented in this reference have limited
practical application because the mass flow ratio which is
used as an independent variable cannot be determined.

Chisholm's work (Reference 11) covers compressible and
incompressible flows with constant area and constant pressure
mixing. Although the ejector flow equations are formulated,
no solution has been attempted for determining the thrust
augmentation ratio.

Reid's investigation (Reference 12) is chiefly aimed at the
reduction of jet noise by means of an ejector; however, an
expression of a so-called thrust parameter is presented. A
simplified theoretical analysis for constant   mixing with
assumed common stagnation temperature for the primary and
secondary streams is presented. The analysis indicates that
although the system of flow equations formulated can be
solved in principle, the numerical solutions are very
difficult to obtain.

The analysis presented in Reference 13 is for a constant
pressure mixing jet ejector with diffuser. The primary and
secondary flows are assumed to have the same stagnation
temperature. As pointed out in this reference, the system
of equations can be solved when the mixing pressure is known.
However, since the mixing pressure is one of the parameters
to be determined, this analysis has no direct practical
application.

Storkebaum in his work (Reference 14) deals with both
incompressible and compressible flow analyses. For the
incompressible case, the idealized thrust augmentation ratio
is presented as a function of the secondary-to-primary area
ratio. The effect of the losses at the entrance to the
mixing chamber is also studied. In the compressible analysis,
the equations for thrust augmentation are formulated;
however, the procedure of solving the equations is not
presented.

Wan performs an incompressible analysis (Reference 15)
similar to that presented by von Kármán (reference 7), with
the exception that the mixed flow velocity at the ejector

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exit is considered to be nonuniform. However, the validity of this analysis appears to be doubtful because, despite the nonuniformity of the exit velocity, the static pressure at the exit is assumed to be uniform.

Payne (Reference 16) conducts a theoretical analysis of a jet ejector with constant pressure mixing treating flows as incompressible. This analysis indicates that the optimum thrust augmentation is primarily dependent on the diffuser efficiency and that augmentation ratios as high as 4.0 or more are possible with high diffuser efficiencies. This conclusion is based on an infinite secondary-to-primary mass flow ratio which cannot be achieved in practice. Also, in performing the differentiation process to obtain optimum thrust augmentation, the analysis uses the pressure in the mixing chamber as the independent variable and considers the mass flow ratio as a constant. This appears to be incorrect, since the mass flow ratio appearing in the basic flow equation is a function of the pressure in the mixing chamber and cannot be treated as a constant. Furthermore, in the breakdown of the location of thrust increase, the analysis indicates that the largest contribution to the total thrust augmentation is due to the bellmouth lip intake rather than the change of momentum of incoming and outgoing flows. No experimental data are presented to justify this conclusion.

Sandover (Reference 17), utilizing the work of Payne (References 16 and 18), performs an analysis also based on one-dimensional incompressible fluid flow. This analysis commences with an assumption that the constant pressure in the mixing chamber can be achieved with a uniform cross section of the chamber; then an attempt is made to determine the optimum exit-to-entrance area ratio. Furthermore, the analysis indicates that an increase in thrust augmentation can be achieved by increasing the temperature of the primary jet flow. This is considered to be incorrect for both the incompressible or compressible flow analyses. In the former case, temperature does not affect the thrust; in the latter case, as indicated in the present report, the increase of the primary jet temperature results in a decrease ratner than an increase of the thrust augmentation ratio. This result has been verified by available experimental data.

From the above review, it is seen that little usable informa-
tion on jet ejector performance is available in the existing
technical literature. Despite the fact that in numerous
investigations, equations representing the ejector flows are
formulated, no explicit solutions are presented for the
practical evaluation of jet ejector performance. In the
cases where some numerical solutions are presented, they are
generally expressed as functions of such parameters as the
mass flow ratio, the pressure at the mixing chamber entrance,
primary jet Mach number, etc., none of which can be readily
determined.

IV. THEORETICAL ANALYSES

As pointed out in the previous section, the presently available literature does not provide adequate information on the thrust augmentation characteristics of jet ejectors. Existing analyses were therefore modified and extended and practical methods were formulated by means of which the potential of jet ejectors can be effectively evaluated.

Because of the complexity of the problem, the following simplifying assumptions are made:

(a) The ejector geometry is axisymmetrical.

(b) The velocity and static pressure of the primary and secondary flow are uniform at the entrance plane to the mixing chamber.

(c) The static pressures of the primary and secondary flows at the entrance to the mixing chamber are equal.

(d) The velocity and static pressure of the mixed flow are uniform at the exit of the mixing chamber, and in the case of an ejector with diffuser are uniform for any cross section of the diffuser.

(e) Both the primary and secondary fluids are perfect gases having the same specific heat.

(f) The pressure at the exit of the mixing chamber, or in the case of a diffuser, at the exit of the diffuser, is equal to the ambient pressure.

(g) The stagnation conditions of the primary flow are unaffected by the presence of the ejector, and the losses in the primary flow up to the exit of the nozzle are neglected.

(h) No heat losses occur at the mixing chamber and diffuser walls.

(i) The motion of the ejector system, if any, is in the same direction as that of the primary jet flow.

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With these simplifying assumptions, the ejector flow field is reduced to a one-dimensional fluid flow problem which can be treated analytically utilizing the following principles of fluid dynamics:

(a) Conservation of mass.

(b) Conservation of energy.

(c) Newton's second law.

(d) Equation of state for perfect gases.

(e) Thermodynamic processes of the flows.

The formulation of the jet ejector flow equations is herein accomplished utilizing Figure 1. As indicated in this figure, various stations of jet ejectors are designated by numbers (0), (1), (2), and (3) which are assigned to represent the respective stations of the jet ejector flows as follows:

Station (0)   Upstream of the entrance of the mixing chamber.

Station (1)   Plane at the entrance of the mixing chamber, which is also the exit plane of the primary nozzle.

Station (2)   Plane at the exit of the mixing chamber, which is also the plane at the entrance of the diffuser.

Station (3)   Plane at the exit of the diffuser.

Utilizing the nomenclature of Figure 1 and the assumptions and conditions described above, the following jet ejector flow equations are obtained:

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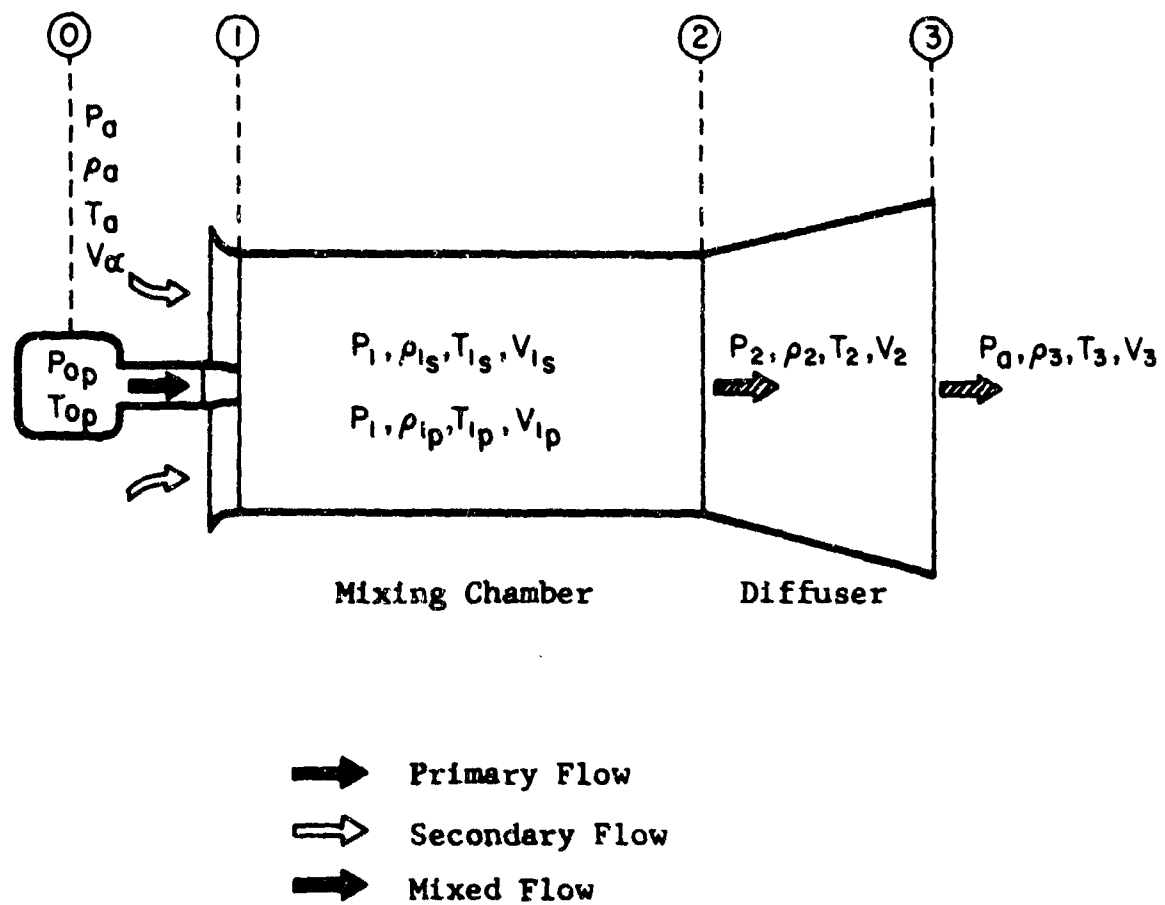
Figure 1. Schematic Representation
of Jet Ejector Configuration.

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Continuity in the Mixing Chamber

$$\rho_{I_p} V_{I_p} + \alpha_E \, \rho_{I_S} V_{I_S} = (\alpha_E + 1) \, \rho_2 V_2 \tag{1}$$

Continuity in the Diffuser

$$\rho_2 V_2 = \alpha_D \rho_3 V_3 \tag{2}$$

Momentum Across the Mixing Chamber

$$(\alpha_E + 1)(P_2 - P_1) = \frac{\rho_{I_p} V_{I_p}^2}{g} + \frac{\alpha_E \rho_{I_p} V_{I_S}^2}{g} - \frac{(\alpha_E + 1)\rho_2 V_2^2}{g} -$$

$$\frac{(\alpha_E + 1)f(L/D)(\rho_{I_S} + \rho_2)(V_{I_S} + V_2)^2}{4g} \tag{3}$$

Conservation of Energy in the Mixing Chamber

$$\rho_{I_p} V_{I_p} c_p T_{O_p} J + \alpha_E \, \rho_{I_S} V_{I_S} c_p T_a J + \frac{V_\alpha^2}{2g})$$

$$= (\alpha_E + 1)\rho_2 V_2 \left(\frac{\gamma}{\gamma - 1} \cdot \frac{P_2}{\rho_2} + \frac{V_2^2}{2g} \right) \tag{4}$$

Conservation of Energy in the Diffuser

$$\frac{\gamma}{\gamma - 1} \cdot \frac{P_2}{\rho_2} + \frac{V_2^2}{2g} = \frac{\gamma}{\gamma - 1} \cdot \frac{P_a}{\rho_3} + \frac{V_3^2}{2g} \tag{5}$$

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Conservation of Energy for the Primary Flow up to the Nozzle Exit

$$c_p \, T_{0_p} \, J = \frac{\gamma}{\gamma - 1} \cdot \frac{P_1}{\rho_{1_p}} + \frac{V_{1_p}^2}{2g} \qquad (6)$$

Conservation of Energy for the Secondary Flow up to the Entrance to the Mixing Chamber

$$c_p T_a \, J + \frac{V_\alpha^2}{2g} = \frac{\gamma}{\gamma - 1} \cdot \frac{P_1}{\rho_{1_S}} + \frac{V_{1_S}^2}{2g} \qquad (7)$$

Isentropic Process of the Primary Flow

$$\frac{P_1}{P_{0_p}} = \left(\frac{\gamma}{\gamma - 1} \cdot \frac{P_1}{\rho_{1_p} c_p T_{0_p} J} \right)^{\frac{\gamma}{\gamma - 1}} \qquad (8)$$

Irreversible Adiabatic Process for the Secondary Flow up to the Entrance to the Mixing Chamber

$$\frac{P_1}{P_a} = \left[\frac{1}{\eta_E} \cdot \frac{\gamma}{\gamma - 1} \cdot \frac{P_1}{\rho_{1_S} c_p T_a J} + \left(1 - \frac{1}{\eta_E} \right) \left(1 - \frac{V_\alpha^2}{2g \, c_p T_a J} \right) \right]^{\frac{\gamma}{\gamma - 1}} \qquad (9)$$

Irreversible Adiabatic Process in the Diffuser

$$\frac{P_2}{P_a} = \left[\frac{\rho_2 \left(\frac{\gamma}{\gamma - 1} \cdot \frac{P_2}{\rho_2} + \eta_D \frac{V_2^2}{2g} \right)}{\rho_3 \left(\frac{\gamma}{\gamma - 1} \cdot \frac{P_2}{\rho_2} + \frac{V_2^2}{2g} \right)} \right]^{\gamma} \qquad (10)$$

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The unknown quantities in the above equations are: P_1, P_2, V_{1p}, V_{1s}, V_2, V_3, ρ_{1p}, ρ_{1s}, P_2, and P_3. The problem basically reduces to a simultaneous solution of 10 nonlinear equations with 10 unknowns. As can be noted, no close-form solution for these equations is possible, and even an iterative solution with the aid of a digital computer is indeed a formidable task.

Hence, in order to obtain a practical evaluation of jet ejector performance, further simplifications are necessary in the analysis.

The present approach consists of first formulating a very simplified analysis, defined herein as the idealized analysis, which enables rapid prediction of maximum thrust augmentation and the entrainment ratio of jet ejectors, for the most idealized flow conditions. The idealized analysis is herein formulated considering perfect fluid flow with no losses and no forward speed effects. This analysis is performed for two types of jet ejectors with constant area mixing and constant pressure mixing.

As a second step, a practical analysis is formulated. This analysis consists of two parts:

    (a)   The effects of major flow losses, forward speed, and diffuser are considered assuming incompressible fluid flow.

    (b)   The effect of flow compressibility is determined on the basis of no flow losses, no diffuser, and no forward speed.

This approach makes it possible to perform with reasonable computational effort a comprehensive parametric study of the relative importance of the individual flow parameters on jet ejector performance and also provides a practical method for the evaluation of various jet ejector systems.

A.   IDEALIZED ANALYSIS

The idealized analysis, which in part is also presented in Reference 7, utilizes the following additional simplifying assumptions:

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(a) The flows are incompressible, which implies that the fluid density is uniform and constant throughout for all the flows and is unaffected by temperature and pressure.

(b) All flow losses are neglected.

(c) The ejector system has no forward speed.

These assumptions apply to both constant area mixing and constant pressure mixing.

1. Constant Area Mixing

The thrust augmentation ratio ϕ is defined as the ratio of the thrust produced with an ejector on F_3 to that produced by the primary jet when it is discharged directly into the atmosphere F_{a_p}.

Thus,

$$\phi = \frac{F_3}{F_{a_p}} \tag{11}$$

where the thrust produced by the ejector is given by

$$F_3 = \frac{\rho}{g} A_3 V_3^2 \tag{12}$$

and the thrust produced by the primary jet discharged directly into the atmosphere is

$$F_{a_p} = \frac{\rho}{g} A_{l_p} V_{a_p}^2 \tag{13}$$

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Substituting equations (12) and (13) into equation (11), there follows

$$\phi = \frac{A_3 V_3^2}{A_{1p} V_{ap}^2}$$ (14)

Applying Bernoulli's equation for the primary flow discharged into the atmosphere and the primary flow discharged into the ejector, and assuming that the stagnation pressure P_{op} is not affected by the presence of the ejector, there results

$$P_{op} = P_a + \frac{1}{2g} \rho V_{ap}^2 = P_{1p} + \frac{1}{2g} \rho V_{1p}^2$$ (15)

Also applying Bernoulli's equation between stations (0) and (1) for the secondary flow,

$$P_a = P_{1s} + \frac{1}{2g} \rho V_{1s}^2$$ (16)

From equations (15) and (16) there results

$$P_{1s} + \frac{1}{2g} \rho V_{1s}^2 + \frac{1}{2g} \rho V_{ap}^2 = P_{1p} + \frac{1}{2g} \rho V_{1p}^2$$ (17)

Using the assumption that $P_{1p} = P_{1s}$, equation (17) reduces to

$$V_{ap}^2 = V_{1p}^2 - V_{1s}^2$$

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or

$$\left(\frac{V_{ap}}{V_{1p}}\right)^2 = 1 - \left(-\frac{V_{1s}}{V_{1p}}\right)^2 \tag{18}$$

Substituting equation (18) into (14) yields

$$\phi = \frac{\left(\dfrac{A_3}{A_{1p}}\right)\left(\dfrac{V_3}{V_{1p}}\right)^2}{1 - \left(\dfrac{V_{1s}}{V_{1p}}\right)^2} \tag{19}$$

The analysis will now proceed to develop the relationships for V_{1s}/V_{1p} and V_3/V_{1p} in terms of the area ratios $\alpha_E = A_{1s}/A_{1p}$ and $\alpha_0 = A_3/A_2 = A_3/(A_{1p} + A_{1s})$

Using the continuity equation between stations (1) and (3), there results

$$A_{1p}V_{1p} + A_{1s}V_{1s} = A_3 V_3 \tag{20}$$

Equation (20) reduces to

$$\frac{V_{1s}}{V_{1p}} = \frac{(\alpha_E + 1)\alpha_0\left(\dfrac{V_3}{V_{1p}}\right) - 1}{\alpha_E} \tag{21}$$

Applying Bernoulli's equation between stations (2) and (3), using P_3 P_a, there follows

$$P_2 + \frac{1}{2g}\rho V_2^2 = P_a + \frac{1}{2g}\rho V_3^2 \tag{22}$$

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Substituting equation (16) into equation (22) yields

$$P_2 = P_{1s} + \frac{1}{2g}\rho V_{1s}^2 + \frac{1}{2g}\rho V_3^2 - \frac{1}{2g}\rho V_2^2 \qquad (23)$$

Also, from momentum considerations between stations (1) and (2), there results

$$A_{1p} P_{1p} + A_{1s} P_{1s} - A_2 P_2 = \frac{\rho}{g} A_2 V_2 - \frac{\rho}{g} A_{1p} V_{1p}^2 - \frac{\rho}{g} A_{1s} V_{1s}^2 \qquad (24)$$

Substituting equation (23) into (24) and using $P_{1p} = P_{1s}$ yields

$$(A_{1p} + A_{1s})P_{1s} - A_2(P_{1s} + \frac{1}{2g}\rho V_{1s}^2 + \frac{1}{2g}\rho V_3^2 - \frac{1}{2g}\rho V_2^2) = \frac{\rho}{g} A_2 V_2^2 - \frac{\rho}{g} A_{1p} V_{1p}^2 - \frac{\rho}{g} A_{1s} V_{1s}^2$$

$$\dots (25)$$

Equation (25) can be simplified as follows

$$\left(\frac{V_{1s}}{V_{1p}}\right)^2 = \frac{(a_E + 1)\left[\left(\frac{V_2}{V_{1p}}\right)^2 + \left(\frac{V_3}{V_{1p}}\right)^2\right] - 2}{a_E - 1} \qquad (26)$$

From continuity equation between stations (2) and (3),

$$V_2 = a_0 V_3 \qquad (27)$$

Squaring equation (27) and substituting into equation (26) yields

$$\left(\frac{V_{1s}}{V_{1p}}\right)^2 = \frac{(a_E + 1)(a_0^2 + 1)\left(\frac{V_3}{V_{1p}}\right)^2 - 2}{a_E - 1} \qquad (28)$$

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Squaring equation (21) and equating it to equation (28), there results the following quadratic equation for V_3/V_{1p} :

$$\left(\frac{V_3}{V_{1p}}\right)^2 - \frac{2(\alpha_E-1)\alpha_D}{\alpha_E^2+\alpha_D^2}\left(\frac{V_3}{V_{1p}}\right) - \frac{2\alpha_E-1}{\alpha_E^2+\alpha_D^2} = 0 \qquad (29)$$

Solving equation (29), the relationship for V_3/V_{1p} is as follows:

$$\left(\frac{V_3}{V_{1p}}\right) = \frac{-(\alpha_E-1)\alpha_D \pm \alpha_E\sqrt{\alpha_D^2+2\alpha_E-1}}{\alpha_E^2+\alpha_D^2} \qquad (30)$$

It can be noted that the velocity ratio V_3/V_{1p} must always be greater than zero for all positive values of the area ratios α_E and α_D. Since $\alpha_D \geq 1$, there follows that for $\alpha_E \geq 0$, the positive sign in front of the second terms must be used. Hence,

$$\left(\frac{V_3}{V_{1p}}\right) = \frac{-(\alpha_E-1)\alpha_D + \alpha_E\sqrt{\alpha_D^2+2\alpha_E-1}}{\alpha_E^2+\alpha_D^2} \qquad (31)$$

Substituting equation (31) into equation (21) yields

$$\left(\frac{V_{1s}}{V_{1p}}\right) = \frac{(\alpha_E+1)\alpha_D\left[-(\alpha_E-1)\alpha_D + \alpha_E\sqrt{\alpha_D^2+2\alpha_E-1}\right]-(\alpha_E^2+\alpha_D^2)}{\alpha_E(\alpha_E^2+\alpha_D^2)} \qquad (32)$$

Finally, substituting equations (31) and (32) into equation (19), the thrust augmentation ratio ϕ can be analytically expressed as follows:

$$\phi = \frac{\alpha_E^2(\alpha_E+1)\alpha_D\left[-(\alpha_E-1)\alpha_D+\alpha_E\sqrt{\alpha_D^2+2\alpha_E-1}\right]^2}{\alpha_E^2(\alpha_E^2+\alpha_D^2)^2-\left\{(\alpha_E+1)\alpha_D\left[-(\alpha_E-1)\alpha_D+\alpha_E\sqrt{\alpha_D^2+2\alpha_E-1}\right]-(\alpha_E^2+\alpha_D^2)\right\}^2}$$

$$\dots(33)$$

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Similarly, the mass entrainment ratio w is given by

$$W = \alpha_E \left(\frac{V_{I_S}}{V_{I_p}} \right) = \frac{(\alpha_E + 1)\, \alpha_D \left[-(\alpha_E - 1)\alpha_D + \alpha_E \sqrt{\alpha_D^2 + 2\alpha_E - 1} \right] - (\alpha_E^2 + \alpha_D^2)}{\alpha_E^2 + \alpha_D^2} \qquad (34)$$

For a special case of constant area mixing condition with no diffuser, i.e., $\alpha_D = 1.0$, the thrust augmentation ratio ϕ reduces to

$$\phi = \frac{(\alpha_E + 1)\left[-(\alpha_E - 1) + \alpha_E \sqrt{2\alpha_E} \right]^2}{(\alpha_E^2 + 1)^2 - \left[-2\alpha_E + (\alpha_E + 1)\sqrt{2\alpha_E} \right]^2} \qquad (35)$$

and the mass entrainment ratio becomes

$$W = \frac{(\alpha_E - 1)\left[-(\alpha_E - 1) + \alpha_E \sqrt{2\alpha_E} \right] - (\alpha_E^2 + 1)}{\alpha_E^2 + 1} \qquad (36)$$

It can be seen from equation (35) that ϕ approaches a limit of 2.0 as α_E tends to infinity. This obviously is not true even under idealized conditions, since an ejector with infinite secondary-to-primary area ratio is equivalent to a free jet discharged into the atmosphere, in which case no thrust augmentation exists and hence $\phi = 1.0$. This discrepancy is attributed to the unrealistic assumption that the secondary velocity at the entrance to the mixing chamber is uniform regardless of the area ratio. A discussion on this subject, together with the derivation of an empirical correction factor for the nonuniform secondary entrance velocity profile, is presented later in this report.

2. Constant Pressure Mixing

The mixing chamber of an ejector is sometimes of variable cross-sectional area. Due to the lack of information on the longitudinal pressure variation inside the mixing chamber, it is, in general, difficult to express the pressure force on the walls in the momentum equation. However, one configuration exists for which an analysis can easily be

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performed. This is the so-called constant pressure mixing configuration which implies that the pressure inside the mixing chamber is considered constant throughout.

Thus, for constant pressure mixing, the additional condition is that the stagnation pressur s P_{l_p}, P_{l_s}, and P_2 are equal and can be denoted as P.

Furthermore, since the contour of the mixing chamber in this case varies such as to maintain the constant pressure requirement, the area at the exit of the mixing chamber A_2 cannot be equated to $A_{l_p} + A_{l_s}$, but must be determined from the analysis.

It should be noted that if the flow from the mixing chamber is directly discharged into the atmosphere, the pressure throughout the ejector would be atmospheric. In such a case, there would be no secondary flow entrainment and, therefore, no thrust augmentation, i.e., $\phi = 1.0$. It therefore follows that a diffuser is required to create a pressure drop in the mixing chamber which would entrain secondary flow in order to produce thrust augmentation ($\phi > 1.0$).

The idealized analysis for constant pressure mixing can be performed in a manner similar to that for constant area mixing. Thus, using equation (19), the relationship for thrust augmentation ratio ϕ can be rewritten in the following form:

$$\phi = \frac{\left(\dfrac{A_3}{A_2}\right)\left(\dfrac{A_2}{A_{l_s}}\right)\left(\dfrac{A_{l_s}}{A_{l_p}}\right)\left(\dfrac{V_3}{V_{l_p}}\right)^2}{1-\left(\dfrac{V_{l_s}}{V_{l_p}}\right)^2}$$

$$= \frac{\alpha_E \, \alpha_D \left(\dfrac{A_2}{A_{l_p}}\right)\left(\dfrac{V_3}{V_{l_p}}\right)^2}{1-\left(\dfrac{V_{l_s}}{V_{l_p}}\right)^2} \tag{37}$$

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In order to obtain the solution for the thrust augmentation ratio for constant pressure mixing, it is now necessary to determine the area ratio A_2/A_{I_s} as well as the velocity ratios V_3/V_{I_p} and V_{I_s}/V_{I_p} . This can be accomplished as follows:

Using the continuity equation between stations (1) and (2), there results

$$A_{I_p}V_{I_p} + A_{I_s}V_{I_s} = A_2V_2 \qquad (38)$$

Also, applying momentum considerations between stations (1) and (2) and considering the constant pressure condition at the mixing chamber walls, there follows

$$PA_{I_p} + PA_{I_s} - PA_2 - \int_{(1)}^{(2)} PdA_n = \frac{\rho A_2 V_2^2}{g} - \frac{\rho A_{I_p} V_{I_p}^2}{g} - \frac{\rho A_{I_s} V_{I_s}^2}{g} \qquad (39)$$

where dA_n is the axial component of the incremental ejector surface area.

The integral $\int_{(1)}^{(2)} PdA_n$ is given by

$$\int_{(1)}^{(2)} PdA_n = P(A_{I_p} + A_{I_s} - A_2) \qquad (40)$$

Substituting equation (40) into (39), there results

$$A_{I_p}V_{I_p}^2 + A_{I_s}V_{I_s}^2 = A_2V_2^2 \qquad (41)$$

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Squaring equation (38) and dividing by equation (41) yields

$$A_2 = \frac{(A_{1p}V_{1p} + A_{1s}V_{1s})^2}{A_{1p}V_{1p}^2 + A_{1s}V_{1s}^2} \tag{42}$$

Equation (42) can be transformed as follows:

$$\left(\frac{A_2}{A_{1s}}\right) = \frac{\left[\frac{1}{\alpha_E} + \left(\frac{V_{1s}}{V_{1p}}\right)\right]^2}{\frac{1}{\alpha_E} + \left(\frac{V_{1s}}{V_{1p}}\right)^2} \tag{43}$$

Using equation (20), the velocity ratio V_{1s}/V_{1p} can be expressed as follows:

$$\left(\frac{V_{1s}}{V_{1p}}\right) = \alpha_0 \left(\frac{A_2}{A_{1s}}\right)\left(\frac{V_3}{V_{1p}}\right) - \frac{1}{\alpha_E} \tag{44}$$

Substituting equation (43) into equation (44) and solving for V_3/V_{1p}, there follows

$$\left(\frac{V_3}{V_{1p}}\right) = \frac{\frac{1}{\alpha_E} + \left(\frac{V_{1s}}{V_{1p}}\right)^2}{\alpha_0 \left[\frac{1}{\alpha_E} + \left(\frac{V_{1s}}{V_{1p}}\right)\right]} \tag{45}$$

Also, from equations (23) and (27) and the constant pressure condition, there results

$$\left(\frac{V_3}{V_{1p}}\right) = \frac{1}{\sqrt{\alpha_0^2 - 1}}\left(\frac{V_{1s}}{V_{1p}}\right) \tag{46}$$

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Equating equations (45) and (46) and simplifying, the following quadratic equation for V_{I_s}/V_{I_p} is obtained:

$$\left(\frac{V_{I_s}}{V_{I_p}}\right)^2 + \frac{\alpha_D}{\alpha_E(\alpha_D - \sqrt{\alpha_D^2-1})} \left(\frac{V_{I_s}}{V_{I_p}}\right) - \frac{\sqrt{\alpha_D^2-1}}{\alpha_E(\alpha_D - \sqrt{\alpha_D^2-1})} = 0 \qquad (47)$$

Solving equation (47) for V_{I_s}/V_{I_p}, there results

$$\left(\frac{V_{I_s}}{V_{I_p}}\right) = \frac{-\alpha_D \pm \sqrt{\alpha_D^2 + 4\alpha_E\sqrt{\alpha_D^2-1}\,(\alpha_D - \sqrt{\alpha_D^2-1})}}{2\alpha_E(\alpha_D - \sqrt{\alpha_D^2-1})} \qquad (48)$$

It can be noted that the velocity ratio V_{I_s}/V_{I_p} must be greater than zero. Since in equation (48) the term

$$\sqrt{\alpha_D^2 + 4\alpha_E\sqrt{\alpha_D^2-1}\,(\alpha_D - \sqrt{\alpha_D^2-1})} > \alpha_D$$

for $\alpha_D > 1.0$ and $\alpha_E > 0$, the velocity ratio V_{I_s}/V_{I_p} will be greater than zero only if the positive sign in front of the square root term is used. Hence,

$$\left(\frac{V_{I_s}}{V_{I_p}}\right) = \frac{-\alpha_D + \sqrt{\alpha_D^2 + 4\alpha_E\sqrt{\alpha_D^2-1}\,(\alpha_D - \sqrt{\alpha_D^2-1})}}{2\alpha_E(\alpha_D - \sqrt{\alpha_D^2-1})} \qquad (49)$$

Finally, substituting equations (43) and (46) into equation (37), the thrust augmentation ratio ϕ for constant pressure mixing can be expressed as a function of area ratios α_E and α_D and the velocity ratio V_{I_s}/V_{I_p}. Thus,

$$\phi = \frac{\alpha_D\left(\frac{V_{I_s}}{V_{I_p}}\right)^2\left[1 + \alpha_E\left(\frac{V_{I_s}}{V_{I_p}}\right)\right]^2}{(\alpha_D^2-1)\left[1 - \left(\frac{V_{I_s}}{V_{I_p}}\right)^2\right]\left[1 + \alpha_E\left(\frac{V_{I_s}}{V_{I_p}}\right)^2\right]} \qquad (50)$$

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where V_{I_S}/V_{I_p} , as given in equation (49), is also a function of the area ratios α_E and α_D only.

Similarly, the mass entrainment ratio w can be expressed as

$$W = \alpha_E \left(\frac{V_{I_S}}{V_{I_p}}\right) = \frac{-\alpha_D + \sqrt{\alpha_D^2 + 4\alpha_E \sqrt{\alpha_D^2 - 1}(\alpha_D - \sqrt{\alpha_D^2 - 1})}}{2(\alpha_D - \sqrt{\alpha_D^2 - 1})} \qquad (51)$$

For the special case of constant pressure mix. , ejector without diffuser, i.e., $\alpha_D = 1.0$, it is evident from equation (49) that $V_{I_S}/V_{I_p} = 0$.

The above result indicates that for the case of no diffuser, i.e., $\alpha_D = 1.0$, there will be no secondary flow and, therefore, no thrust augmentation.

B. PRACTICAL ANALYSIS

Presented in this section is a practical analysis which includes the effects of many important jet ejector flow parameters neglected in the idealized approach yet yields solutions with a relatively reasonable computational effort. This analysis pertains to a jet ejector with constant area mixing having a conical diffuser attached to the exit of the mixing chamber.

As mentioned previously, the practical analysis is performed in the following stages:

1. The Incompressible Analysis With Flow Losses

Although this analysis is based on the incompressible fluid flow conditions, it includes the following practical operating conditions and flow losses:

    (a) Effect of forward speed (parallel to ejector walls).

    (b) Effect of diffuser.

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(c) The total head loss at the secondary entrance to
     the mixing chamber.

(d) The friction head loss at the mixing chamber walls.

(e) Total head loss in the diffuser.

For the incompressible analysis including the flow losses
and the operating conditions specified above, the jet ejector
flow equations (1) through (10) can be reduced to the
following:

Continuity in the Mixing Chamber

$$V_{1_p} + \alpha_E V_{1_S} = (\alpha_E + 1) V_2 \tag{52}$$

Continuity in the Diffuser

$$V_2 = \alpha_D V_3 \tag{53}$$

Momentum Across the Mixing Chamber

$$(\alpha_E + 1)(P_2 - P_1) = \frac{\rho V_{1_p}^2}{g} + \frac{\alpha_E \rho V_{1_S}^2}{g} -$$
$$\frac{(\alpha_E + 1)\rho V_2^2}{g} - \frac{(\alpha_E + 1) f(L/D)\rho (V_{1_S} + V_2)^2}{2g} \tag{54}$$

Bernoulli's Equation for the Secondary Flow up to
the Entrance to the Mixing Chamber

$$P_0 + \frac{\rho V \alpha^2}{2g} = P_1 + \frac{\rho(1 + \lambda_E) V_{1_S}^2}{2g} \tag{55}$$

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Bernoulli's Equation for the Flow in the Diffuser

$$P_2 + \frac{\rho\left[(\alpha_0^2-1)-\lambda_0(\alpha_0-1)^2\right]V_3^2}{2g} = P_a \tag{56}$$

The solution of the system of five equations, (52) through (56), is similar to that presented above for the idealized theoretical analysis. In the final analysis, the five equations can be reduced to one quadratic equation for the nondimensional mixed flow velocity at the exit of the diffuser V_3/V_{1p}. This equation is

$$\left\{(\alpha_E^2+\alpha_0^2)+\mu^2\left[\alpha_E^2(\alpha_0^2-1)+2\alpha_E\alpha_0^2\right]+\right.$$

$$\left[\lambda_E(\alpha_E+1)^2\alpha_0^2+f(L/D)(2\alpha_E+1)^2\alpha_0^2+\lambda_0\alpha_E^2(\alpha_0-1)^2\right]-$$

$$\left.\mu^2\left[f(L/D)(2\alpha_E+1)^2\alpha_0^2+\lambda_0\alpha_E^2(\alpha_0^2-1)\right]\right\}\left(\frac{V_3}{V_{1p}}\right)^2+$$

$$\left\{2(\alpha_E-1)\alpha_0-4\mu^2\alpha_E\alpha_0-2\left[f(L/D)(2\alpha_E+1)\alpha_0+\lambda_E(\alpha_E+1)\alpha_0^2\right]+\right.$$

$$\left.2\mu^2f(L/D)(2\alpha_E+1)\alpha_0\right\}\left(\frac{V_3}{V_{1p}}\right)-$$

$$\left\{(2\alpha_E-1)+\mu^2\alpha_E(\alpha_E-2)-\left[\lambda_E+f(L/D)\right]+\mu^2f(L/D)\right\}=0 \tag{57}$$

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Also, the nondimensionalized secondary velocity ratio V_{1s}/V_{1p} is given by

$$\left(\frac{V_{1s}}{V_{1p}}\right) = \frac{(\alpha_E+1)\alpha_D\left(\frac{V_3}{V_{1p}}\right)-1}{\alpha_E} \qquad (58)$$

The thrust augmentation ratio ϕ for the ejector with forward speed V_α is given by

$$\phi = \frac{(\alpha_E+1)\alpha_D V_3(V_3-V_\alpha)+V_{1p}V_\alpha}{V_{0p}^2} \qquad (59)$$

Equation (59) can be expressed in the following form:

$$\phi = \frac{1}{\alpha_E^2-(1+\lambda_E)\left[(\alpha_E+1)\alpha_D\left(\frac{V_3}{V_{1p}}\right)-1\right]^2}\left\{\alpha_E^2(\alpha_E+1)(1-\mu^2)\alpha_D\left(\frac{V_3}{V_{1p}}\right)-\right.$$

$$\left. \mu\,\alpha_E\left[(\alpha_E+1)\alpha_D\left(\frac{V_3}{V_{1p}}\right)-1\right]\sqrt{\left\{\alpha_E^2-(1+\lambda_E)\left[(\alpha_E+1)\alpha_D\left(\frac{V_3}{V_{1p}}\right)-1\right]^2\right\}(1-\mu^2)} \right\}$$

$$\qquad \ldots (60)$$

where

$$\mu = \frac{V_\alpha}{V_{0p}} \qquad (61)$$

The mass entrainment ratio w is

$$W = \alpha_E\left(\frac{V_{1s}}{V_{1p}}\right) \qquad (62)$$

The above analysis is utilized to determine the effects of various flow losses, diffuser area ratios, and forward speed.

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2. Effect of Flow Compressibility

As discussed previously, the effect of flow compressibility
is treated assuming no losses, no diffuser, and no forward
speed. This analysis utilizes the flow equations (1)
through (10), with the following conditions:

$$\left.\begin{array}{c} V_\alpha = f(L/D) = \lambda_E = \lambda_D = 0 \\[2mm] a_D = \eta_E = \eta_D = 1.0 \\[2mm] P_2 = P_a \end{array}\right\} \qquad (63)$$

Using the above stipulated conditions, the jet ejector flow
equations (1) through (10) can now be reduced to seven
equations with seven unknowns, which are $\rho_{1p}, \rho_{1s}, \rho_2, V_{1p},$
V_{1s}, V_2, and P_1. These equations in their non-
dimensionalized form are as follows:

Continuity in the Mixing Chamber

$$\left(\frac{\rho_{1p}}{\rho_{ap}}\right)\left(\frac{V_{1p}}{V_{ap}}\right) + a_E\left(\frac{\rho_{1s}}{\rho_{ap}}\right)\left(\frac{V_{1s}}{V_{ap}}\right) = (a_E+1)\left(\frac{\rho_2}{\rho_{ap}}\right)\left(\frac{V_2}{V_{ap}}\right) \qquad (64)$$

Momentum Across the Mixing Chamber

$$\frac{(a_E+1)(P_a-P_1)}{\rho_{ap}V_{ap}^2} = \frac{1}{g}\left(\frac{\rho_{1p}}{\rho_{ap}}\right)\left(\frac{V_{1p}}{V_{ap}}\right)^2 + \frac{a_E}{g}\left(\frac{\rho_{1s}}{\rho_{ap}}\right)\left(\frac{V_{1s}}{V_{ap}}\right)^2 - \frac{(a_E+1)}{g}\left(\frac{\rho_2}{\rho_{ap}}\right)\left(\frac{V_2}{V_{ap}}\right)^2$$

$$\dots(65)$$

Conservation of Energy in the Mixing Chamber

$$\left(\frac{\rho_{1p}}{\rho_{ap}}\right)\left(\frac{V_{1p}}{V_{ap}}\right) + a_E\left(\frac{\rho_{1s}}{\rho_{ap}}\right)\left(\frac{V_{1s}}{V_{ap}}\right)\left(\frac{T_a}{T_{op}}\right) = \frac{(a_E+1)}{c_pT_{op}J}\left(\frac{\rho_2}{\rho_{ap}}\right)\left(\frac{V_2}{V_{ap}}\right)\left(\frac{\gamma}{\gamma-1}\cdot\frac{P_2}{\rho_2}+\frac{V_2^2}{2g}\right)$$

$$\dots(66)$$

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Conservation of Energy for the Primary Flow up to the Nozzle Exit

$$\frac{2gc_p T_{O_p} J}{V_{a_p}^2} = \frac{2gc_p T_{I_p} J}{V_{a_p}^2} + \left(\frac{V_{I_p}}{V_{a_p}}\right)^2 \tag{67}$$

Conservation of Energy for the Secondary Flow up to the Entrance to the Mixing Chamber

$$\frac{2gc_p T_{a} J}{V_{a_p}^2} = \frac{2gc_p T_{I_s} J}{V_{a_p}^2} + \left(\frac{V_{I_s}}{V_{a_p}}\right)^2 \tag{68}$$

Isentropic Process of the Primary Flows

$$\frac{P_I}{P_{O_p}} = \left[\frac{\gamma}{\gamma-1} \cdot \frac{P_I}{\rho_{I_p} c_p T_{O_p} J}\right]^{\frac{\gamma}{\gamma-1}} \tag{69}$$

Isentropic Process of the Secondary Flow

$$\frac{P_I}{P_a} = \left[\frac{\gamma}{\gamma-1} \cdot \frac{P_I}{\rho_{I_s} c_p T_a J}\right]^{\frac{\gamma}{\gamma-1}} \tag{70}$$

In these equations, ρ_{a_p} and V_{a_p} refer to the density and velocity, respectively, for the primary jet exhausted directly to the ambient and are given by

$$\rho_{a_p} = \frac{\gamma}{\gamma-1} \cdot \frac{P_a}{c_p T_{O_p} J} \left(\frac{P_{O_p}}{P_a}\right)^{\frac{\gamma-1}{\gamma}} \tag{71}$$

$$V_{a_p} = \sqrt{2gc_p T_{O_p} J \left[1 - \left(\frac{P_a}{P_{O_p}}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{72}$$

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The solution of the system of equations (64) through (70) is performed as follows:

From equations (69) and (70),

$$\left(\frac{\rho_{1s}}{\rho_{a_p}}\right) = \frac{\left(\dfrac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}}}{\left(\dfrac{T_a}{T_{o_p}}\right)} \tag{73}$$

Substituting equation (72) into equation (67), there follows

$$\left(\frac{V_{1p}}{V_{a_p}}\right)^2 = \frac{1-\left(\dfrac{T_{1p}}{T_{o_p}}\right)}{1-\left(\dfrac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}}} \tag{74}$$

Since

$$\left(\frac{T_{1p}}{T_{o_p}}\right) = \left(\frac{T_{1p}}{T_{a_p}}\right)\left(\frac{T_{a_p}}{T_{o_p}}\right)$$

and

$$\left(\frac{T_{a_p}}{T_{o_p}}\right) = \left(\frac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\therefore \left(\frac{T_{1p}}{T_{o_p}}\right) = \left(\frac{T_{1p}}{T_{a_p}}\right)\left(\frac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}} \tag{75}$$

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Substituting equation (75) into equation (74) yields

$$\left(\frac{V_{1p}}{V_{ap}}\right)^2 = \frac{1-\left(\frac{T_{1p}}{T_{ap}}\right)\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}}{1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}} \qquad (76)$$

Similarly, substituting equation (72) into equation (68), there follows

$$\left(\frac{V_{1s}}{V_{ap}}\right)^2 = \frac{\left(\frac{T_a}{T_{op}}\right)\left[1-\left(\frac{T_{1s}}{T_a}\right)\right]}{1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}} \qquad (77)$$

Since

$$\left(\frac{T_{1s}}{T_a}\right) = \left(\frac{P_{1s}}{P_a}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\left(\frac{T_{1p}}{T_a}\right) = \left(\frac{P_{1p}}{T_{ap}}\right)^{\frac{\gamma-1}{\gamma}}$$

and

$$P_{1p} = P_{1s} = P_1$$

$$\therefore \quad \left(\frac{T_{1s}}{T_a}\right) = \left(\frac{T_{1p}}{T_{ap}}\right) \qquad (78)$$

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Substituting equation (78) into equation (77) yeilds

$$\left(\frac{V_{l_s}}{V_{a_p}}\right)^2 = \frac{\left(\frac{T_a}{T_{o_p}}\right)\left[1-\left(\frac{T_{l_p}}{T_{a_p}}\right)\right]}{1-\left(\frac{P_a}{P_{o_p}}\right)^{\frac{1}{\gamma-1}}} \tag{79}$$

Using the basic isentropic relationship,

$$\left(\frac{\rho_{l_p}}{\rho_{a_p}}\right) = \left(\frac{T_{l_p}}{T_{a_p}}\right)^{\frac{1}{\gamma-1}} \tag{80}$$

Substituting equation (80) into (73) yields

$$\left(\frac{\rho_{l_s}}{\rho_{a_p}}\right) = \frac{\left(\frac{T_{l_p}}{T_{a_p}}\right)^{\frac{1}{\gamma-1}}\left(\frac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}}}{\left(\frac{T_a}{T_{o_p}}\right)} \tag{81}$$

From the equation of state,

$$P_a = \frac{\gamma-1}{\gamma} c_p \rho_{a_p} T_{a_p} J$$

$$= \frac{\gamma-1}{\gamma} c_p \rho_{a_p} T_{o_p}\left(\frac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}} J \tag{82}$$

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Also, from the isentropic relationship,

$$\frac{P_1}{P_a} = \left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{\gamma}{\gamma-1}}$$

(83)

Substituting equation (82) into equation (83), there follows

$$P_1 = \frac{\gamma-1}{\gamma} c_p \rho_{ap} T_{op} \left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}} \left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{\gamma}{\gamma-1}} J$$

(84)

Making use of equation (64) and substituting equations (76), (77), (80), (81), (82), and (84) into equation (65), there results

$$\left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{1}{\gamma-1}} \left\{ \sqrt{\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\right]\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{1p}}{T_{ap}}\right)\right]} + \right.$$

$$\left. \alpha_E \left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}} \sqrt{\frac{\left[1-\left(\frac{T_{1p}}{T_{ap}}\right)\right]\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\right]}{\left(\frac{T_a}{T_{op}}\right)}} \right\} \left(\frac{V_2}{V_{ap}}\right) -$$

$$\left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{1}{\gamma-1}} \left\{ 1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{1p}}{T_{ap}}\right) + \alpha_E \left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left[1-\left(\frac{T_{1p}}{T_{ap}}\right)\right] \right\} +$$

$$\left(\frac{\alpha_E+1}{2}\right) \left(\frac{\gamma}{\gamma-1}\right) \left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}} \left[1-\left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{\gamma}{\gamma-1}}\right] = 0$$

(85)

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Similarly, equation (66) can be transformed as follows:

$$
\left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{1}{\gamma-1}}\left\{\sqrt{\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\right]\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{1p}}{T_{ap}}\right)\right]} + \right.
$$

$$
\left. \alpha_E\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\sqrt{\frac{\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\right]\left[1-\left(\frac{T_{1p}}{T_{ap}}\right)\right]}{\left(\frac{T_a}{T_{op}}\right)}}\right\}\left(\frac{V_2}{V_{ap}}\right)^2 +
$$

$$
(\alpha_E+1)\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{V_2}{V_{ap}}\right) -
$$

$$
\left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{1}{\gamma-1}}\left\{\sqrt{\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\right]\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{1p}}{T_{ap}}\right)\right]} + \right.
$$

$$
\left. \alpha_E\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\sqrt{\left(\frac{T_a}{T_{op}}\right)\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\right]\left[1-\left(\frac{T_{1p}}{T_{ap}}\right)\right]}\right\} = 0 \quad (86)
$$

Equations (85) and (86) are the two final equations which contain the unknowns T_{1p}/V_{ap} and V_2/V_{ap} and can be solved by an iteration method. It is seen that c_p, the specific heat at constant pressure, no longer appears in the equations.

The thermodynamic properties of the flows at different stations along the ejector can be expressed in terms of T_{1p}/T_{ap} and V_2/V_{ap} as follows:

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$$\left(\frac{V_{1p}}{V_{ap}}\right) = \sqrt{\frac{1-\left(\frac{P_a}{P_{0p}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{1p}}{T_{ap}}\right)}{1-\left(\frac{P_a}{P_{0p}}\right)^{\frac{\gamma-1}{\gamma}}}} \tag{87}$$

$$\left(\frac{V_{1s}}{V_{ap}}\right) = \sqrt{\frac{\left(\frac{T_a}{T_{0p}}\right)\left[1-\left(\frac{T_{1p}}{T_{ap}}\right)\right]}{1-\left(\frac{P_a}{P_{0p}}\right)^{\frac{\gamma-1}{\gamma}}}} \tag{88}$$

$$\left(\frac{\rho_{1p}}{\rho_{ap}}\right) = \left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{1}{\gamma-1}} \tag{89}$$

$$\left(\frac{\rho_{1s}}{\rho_{ap}}\right) = \frac{\left(\frac{P_a}{P_{0p}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{1}{\gamma-1}}}{\left(\frac{T_a}{T_{0p}}\right)} \tag{90}$$

$$\left(\frac{\rho_2}{\rho_{ap}}\right) = \frac{\left(\frac{\rho_{1p}}{\rho_{ap}}\right)\left(\frac{V_{1p}}{V_{ap}}\right)+\alpha_E\left(\frac{\rho_{1s}}{\rho_{ap}}\right)\left(\frac{V_{1s}}{V_{ap}}\right)}{(\alpha_E+1)\left(\frac{V_2}{V_{ap}}\right)} \tag{91}$$

$$\left(\frac{T_{1s}}{T_{ap}}\right) = \frac{\left(\frac{T_{1p}}{T_{ap}}\right)\left(\frac{T_a}{T_{0p}}\right)}{\left(\frac{P_a}{P_{0p}}\right)^{\frac{\gamma-1}{\gamma}}} \tag{92}$$

$$\left(\frac{T_2}{T_{ap}}\right) = \frac{1}{\left(\frac{\rho_2}{\rho_{ap}}\right)} \tag{93}$$

$$\left(\frac{P_1}{P_a}\right) = \left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{\gamma}{\gamma-1}} \tag{94}$$

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$$M_{l_p} = \sqrt{\frac{2}{\gamma-1}\left[\frac{1-\left(\frac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{l_p}}{T_{a_p}}\right)}{\left(\frac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{l_p}}{T_{a_p}}\right)}\right]} \tag{95}$$

$$M_{l_s} = \sqrt{\frac{2}{\gamma-1}\left[\frac{1}{\left(\frac{T_{l_p}}{T_{a_p}}-1\right)}\right]} \tag{96}$$

$$M_2 = \sqrt{\frac{2}{\gamma-1}\left(\frac{\rho_2}{\rho_{a_p}}\right)\left[\frac{1-\left(\frac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}}}{\left(\frac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}}}\right]} \tag{97}$$

Finally, the thrust augmentation ratio ϕ and the mass entrainment ratio w can be determined as follows:

$$\phi = (\alpha_E + 1)\left(\frac{\rho_2}{\rho_{a_p}}\right)\left(\frac{V_2}{V_{a_p}}\right)^2 \tag{98}$$

$$W = \alpha_E \frac{\left(\frac{\rho_{l_s}}{\rho_{a_p}}\right)\left(\frac{V_{l_s}}{V_{a_p}}\right)}{\left(\frac{\rho_{l_p}}{\rho_{a_p}}\right)\left(\frac{V_{l_p}}{V_{a_p}}\right)} \tag{99}$$

3. Nonuniform Velocity Profile at the Secondary Entrance

In both the idealized and practical analyses, a one-dimensional approach is used which assumes the secondary flow

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velocity at the entrance plane as uniform, irrespective of the secondary-to-primary area ratio. For the case of no diffuser, the idealized analysis yields a maximum thrust augmentation ratio of 2.0 at an infinite area ratio. This is obviously not correct, because when the area ratio tends to infinity, the ejector configuration reduces to a free jet, in which case the augmentation ratio must be unity. It is believed that this discrepancy is caused by the assumption of the uniform flow velocity at the secondary entrance. In other words, the applicability of the one-dimensional approach is limited to not too large secondary-to-primary area ratios, and a three-dimensional analysis is required for relatively large area ratios. However, such a task has never been undertaken by any of the investigators, and it is beyond the scope of this program to formulate a solution to this complex problem.

Instead, an empirical correction factor is herein developed to account for the effect of the nonuniform secondary flow velocity profile. The derivation of this factor is as follows:

Under the assumption of uniform secondary flow velocity, the momentum equation for the control volume inside the mixing chamber with no diffuser and no losses becomes:

$$(\alpha_E + 1)(P_a - \overline{P}_1) = \frac{\rho}{g}\left[\overline{V}_{1_p}^2 + \alpha_E \overline{V}_{1_S}^2 - (\alpha_E + 1)\overline{V}_2^2\right] \tag{100}$$

By using Bernoulli's equation for the secondary flow and the ambient conditions in front of the ejector, equation (100) is reduced to

$$\left(\frac{\overline{V}_2}{\overline{V}_{1_p}}\right)^2 = \frac{1 + \left(\frac{\alpha_E - 1}{2}\right)\left(\frac{\overline{V}_{1_S}}{\overline{V}_{1_p}}\right)^2}{\alpha_E + 1} \tag{101}$$

In these equations, the "bar" denotes uniform values.

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If the secondary velocity is not uniform, the momentum equation becomes

$$(\alpha_E + 1) P_0 - \overline{P}_1 - \frac{\alpha_E \int P_{I_s} dA_{I_s}}{A_{I_s}}$$

$$= \frac{\rho}{g} \left[\overline{V}_{I_p}^2 + \frac{\int V_{I_s}^2 dA_{I_s}}{A_{I_s}} - (\alpha_E + 1) V_2^2 \right] \qquad (10\ )$$

The solution of equation (102) for $(V_2/\overline{V}_{I_p})$ is based on the following assumptions:

(a) The primary velocity at the entrance plane is still the same as in the case of uniform secondary velocity.

(b) The primary pressure at the entrance plane is the same as in the case of uniform secondary velocity. Hence, $\overline{P}_{I_p} = \overline{P}_1$

(c) The exit velocity of the mixed flow V_2, though different from that in the case of uniform secondary velocity, is uniform at the mixing chamber exit.

Since the secondary flow has a uniform stagnation pressure P_0 far upstream, by assuming parallel streamlines at the entrance plane it is possible to evaluate the static pressure distribution P_{I_s} by making use of Bernoulli's equation. Thus, equation (102) is finally reduced to

$$\left(\frac{V_2}{\overline{V}_{I_p}}\right)^2 = \frac{1 + \dfrac{\alpha_E \int \left(\dfrac{V_{I_s}}{\overline{V}_{I_p}}\right)^2 dA_{I_s}}{2 A_{I_s}} - \dfrac{1}{2} \left(\dfrac{\overline{V}_{I_s}}{\overline{V}_{I_p}}\right)^2}{\alpha_E + 1} \qquad (103)$$

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Equations (101) and (103) yield the exit-to-primary velocity ratios based on uniform and nonuniform secondary entrance velocity profiles, respectively. The corresponding thrust augmentation ratios for the two cases are given below.

The thrust augmentation ratio for the case of uniform secondary velocity is

$$\bar{\phi} = \frac{(\alpha_E + 1)\left(\frac{\bar{V}_2}{\bar{V}_{1p}}\right)^2}{\left(\frac{\bar{V}_{ap}}{\bar{V}_{1p}}\right)^2} \tag{104}$$

where $\bar{V}_{ap}/\bar{V}_{1p}$ and $\bar{V}_2/\bar{V}_{1p}$ can be obtained from the idealized theoretical analysis as follows:

$$\left(\frac{\bar{V}_{ap}}{\bar{V}_{1p}}\right)^2 = 1 - \frac{2\left[(\alpha_E + 1)\left(\frac{\bar{V}_2}{\bar{V}_{1p}}\right)^2 - 1\right]}{\alpha_E - 1} \tag{105}$$

and

$$\left(\frac{\bar{V}_2}{\bar{V}_{1p}}\right)^2 = \left[\frac{-(\alpha_E - 1) + \alpha_E \sqrt{2\alpha_E}}{\alpha_E^2 + 1}\right]^2 \tag{106}$$

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For the nonuniform case, the thrust augmentation ratio is

$$\phi = \frac{(\alpha_E + 1)\left(\dfrac{V_2}{\overline{V}_{1p}}\right)^2}{\left(\dfrac{\overline{V}_{ap}}{\overline{V}_{1p}}\right)^2} \qquad (107)$$

where $\left(V_2/\overline{V}_{1p}\right)^2$ as given by equation (103) will be determined below.

The correction factor for thrust augmentation ratio due to nonuniform velocity profile at the secondary entrance is herein defined as

$$\chi = \frac{\phi}{\overline{\phi}} = \frac{\left(\dfrac{V_2}{\overline{V}_{1p}}\right)^2}{\left(\dfrac{\overline{V}_2}{\overline{V}_{1p}}\right)^2} \qquad (108)$$

It is now necessary to establish relationships for $V_{1s}/\overline{V}_{1p}$ and $\overline{V}_{1s}/\overline{V}_{1p}$ to determine $V_2/\overline{V}_{1p}$ given by equation (103). According to Reference 26, the velocity profile of a flow entrained by a free jet can be well approximated by a cosine curve. Therefore, it is reasonable to assume that a cosine curve distribution, as shown in Figure 2, will adequately represent the velocity profile at the secondary entrance of a jet ejector system.

It is further assumed that the local secondary velocity at the jet periphery ⓐ is the same as the uniform velocity $\overline{V}_{1s}$. Thus, the secondary entrance velocity profile at any radial station can be expressed as follows:

$$V_{1s} = \frac{1 + \cos\dfrac{(r'-1)\,\pi}{\kappa}}{2}\,\overline{V}_{1s} \qquad (109)$$

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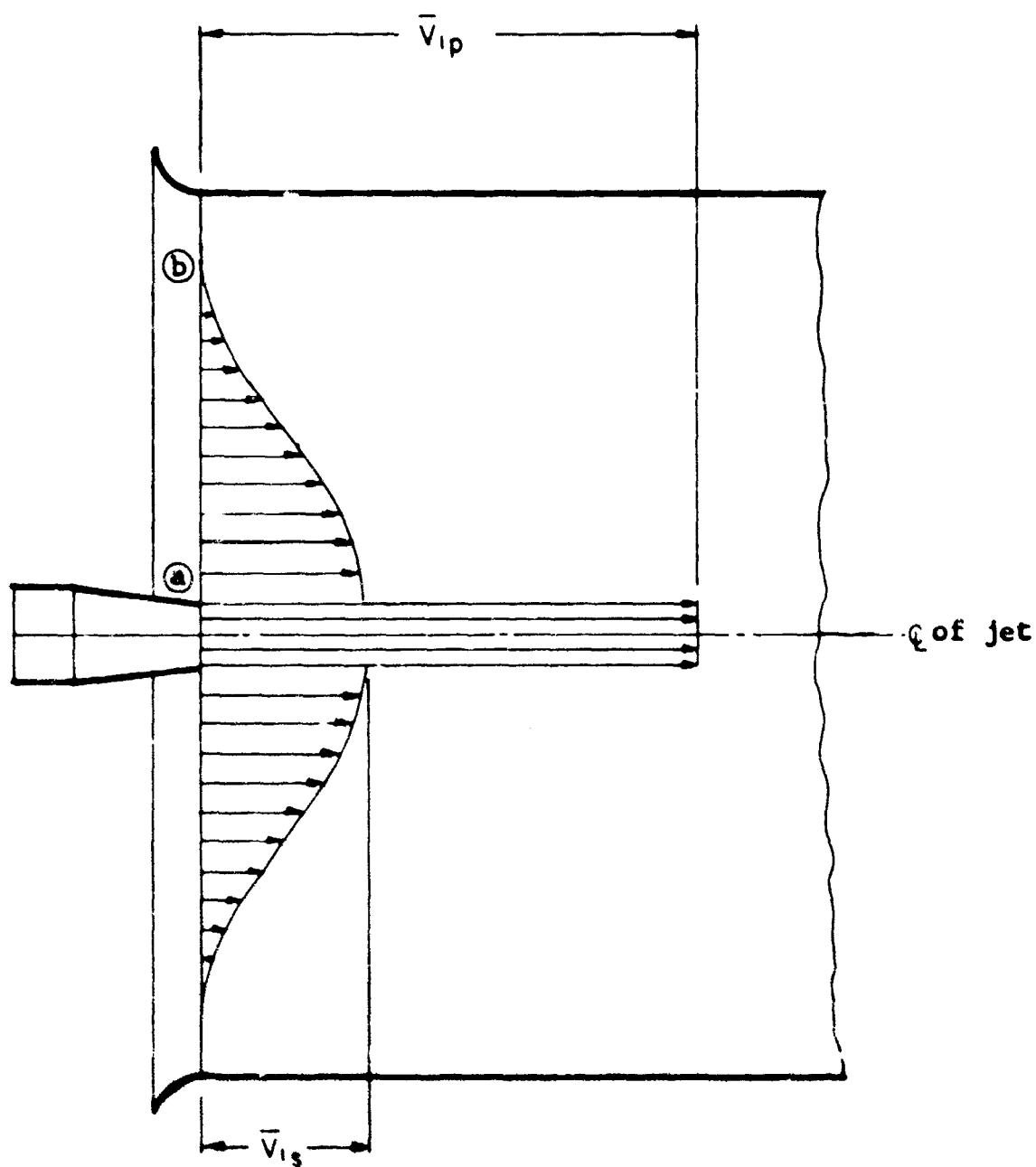
Figure 2. Nonuniform Velocity Profile at Secondary Entrance.

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In equation (109), r' is the radial distance from the ejector center line, nondimensionalized by the jet radius, and κ, is a constant defining flow nonuniformity at the secondary entrance. This equation applies only for the range $0 \leq (r'-1)/\kappa \leq 1$. In other words, as shown in **Figure 2**, the local velocity V_{ls} gradually decreases to zero at point ⓑ and maintains zero at any larger radial distance from the ejector center line. The location of point ⓑ depends on the constant κ.

By assigning a suitable value of κ, the integral $\int (V_{ls}/\overline{V}_{lp})^2 \, dA_{ls}/A_{ls}$ in equation (103) can be evaluated for all values of α_E in terms of $\overline{V}_{ls}$. Let

$$\xi = \frac{\int V_{ls}^2 \, dA_{ls}}{\overline{V}_{ls}^2 A_{ls}} \tag{110}$$

Substituting equation (109) into equation (110), there results

$$\xi = \frac{\alpha_E + 1}{2} \int_0^1 \left[1 + \cos \frac{(r'-1)\pi}{\kappa} \right] r' \, dr' \tag{111}$$

Integrating equation (111) with respect to r' yields

$$\xi = \frac{3}{8} + \frac{\kappa \sqrt{\alpha_E + 1}}{4 \alpha_E \pi} \sin \frac{(\sqrt{\alpha_E + 1} - 1)\pi}{\kappa} \left[4 + \cos \frac{(\sqrt{\alpha_E + 1} - 1)\pi}{\kappa} \right] -$$

$$\frac{\kappa^2}{8 \alpha_E \pi^2} \left[1 - \cos \frac{(\sqrt{\alpha_E + 1} - 1)\pi}{\kappa} \right] \left[9 + \cos \frac{(\sqrt{\alpha_E + 1} - 1)\pi}{\kappa} \right] \tag{112}$$

for $\alpha_E \leq \kappa (\kappa + 2)$ and

$$\xi = \frac{3\kappa (\kappa + 2) \pi^2 - 16 \kappa^2}{8 \alpha_E \pi^2} \tag{113}$$

for $\alpha_E \leq \kappa (\kappa + 2)$

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The correction factor for the thrust augmentation ratio given by equation (108) thus becomes

$$\chi = \frac{1 + \dfrac{\xi}{2} \dfrac{\alpha_E - 1}{2} \left(\dfrac{\overline{V}_{1s}}{\overline{V}_{1p}}\right)^2}{1 + \dfrac{\alpha_E - 1}{2} \left(\dfrac{\overline{V}_{1s}}{\overline{V}_{1p}}\right)^{\!\!\!\cdot}} \tag{114}$$

where ξ is given by equation (112) or (113) and $\overline{V}_{1s}/\overline{V}_{1p}$ can be obtained from the idealized analysis equation (32) as follows:

$$\frac{\overline{V}_{1s}}{\overline{V}_{1p}} = \frac{(\alpha_E + 1)\left[-(\alpha_E - 1) + \alpha_E \sqrt{2\alpha_E}\right] - (\alpha_E^2 + 1)}{\alpha_E(\alpha_E^2 + 1)} \tag{115}$$

Equation (114) is utilized to compute the thrust augmentation ratio ϕ as affected by the nonuniform velocity distribution at the secondary entrance. The results are herein presented in Figure 3, which shows the variation of ϕ vs. α_E for constant values of the parameter κ. By examining this figure, it can be noted that as κ tends to infinity, the ϕ vs. α_E relationship reduces to that as obtained by the idealized analysis with uniform secondary velocity profile. Also, for any finite value of κ, ϕ reaches a maximum value (less than 2.0) at a finite α_E and then decreases to unity as α_E tends to infinity.

In order to determine the parameter κ, appropriate test data are required which could be used to determine the area ratio α_E at which the thrust augmentation ratio is maximum. However, most of the available test data (see Section VI) are obtained for ejectors having area ratios α_E of less than 100, at which values the thrust augmentation ratio ϕ does not reach a maximum value. For example, the correlation shown in Table II (Section VII) indicates that at an area ratio of $\alpha_E = 104$, the rate of increase of ϕ with α_E is quite small. It is reasonable to assume, therefore, that for α_E ranging

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Figure 3. Effect of κ on Thrust Augmentation Ratio.

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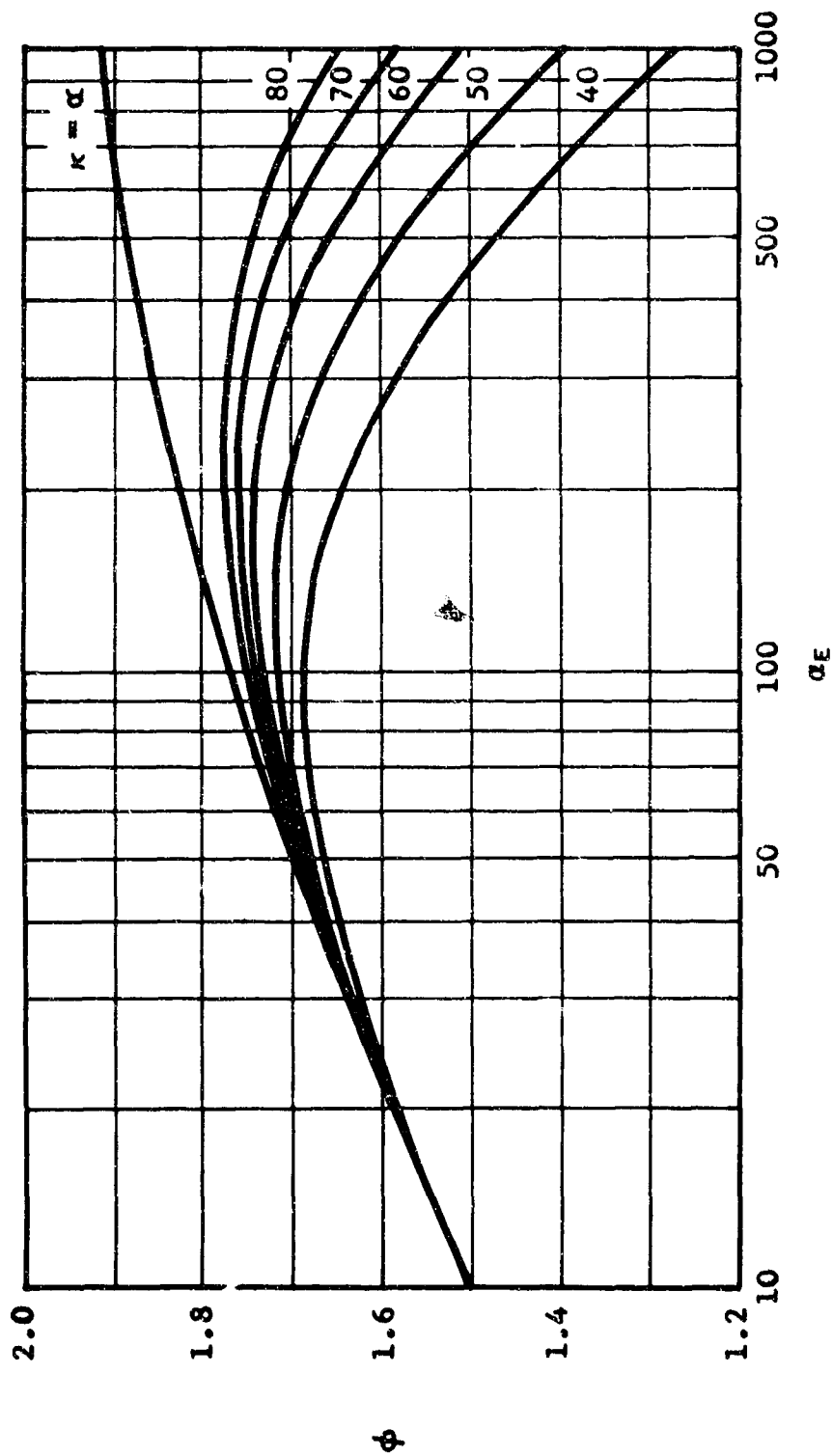
from 150 to 200, the thrust augmentation would have reached its peak value. Therefore, it follows from Figure 3 that a practical value of the parameter κ would be between $\kappa = 60$ and $\kappa = 70$. This, however, necessitates further experimental evidence.

4. Analysis of Various Ejector Types

The most common types of jet ejectors consist of either single nozzle, multiple nozzle, or annular nozzle configurations. These configurations differ from each other primarily in the efficiency at which the primary, low momentum flow is converted into a high momentum flow. The conversion takes place in the mixing chamber, which, in order to reduce wall friction losses, should be of minimum length. No precise method exists at present to determine the minimum mixing chamber length required to achieve complete mixing between the primary and secondary flows. The following analysis will provide, however, a first-order approximation of the relative effects of the different configurations on the mixing chamber length.

First, it is assumed that the mixing chamber consists of two parts as shown in Figure 4. The first part (L_1), which allows for the primary jet expansion, starts at the jet exit and ends at a point where the jet boundary reaches the ejector walls. The second part (L_2) starts from thereon and extends to the exit of the mixing chamber, where the mixing process is assumed to be completed.

a. Single Nozzle Configuration

The work of Squire and Trouncer (Reference 19) is utilized to determine the length (L_1) for a single-nozzle primary flow configuration.

In this reference an analysis is performed for determining the expansion angle of a single, circular jet discharging into a free stream of uniform velocity. If it is assumed that this expansion angle is not affected by the presence of the mixing chamber walls, the primary jet boundaries can be plotted as a function of the secondary flow velocity as shown in Figure 5. In this figure the

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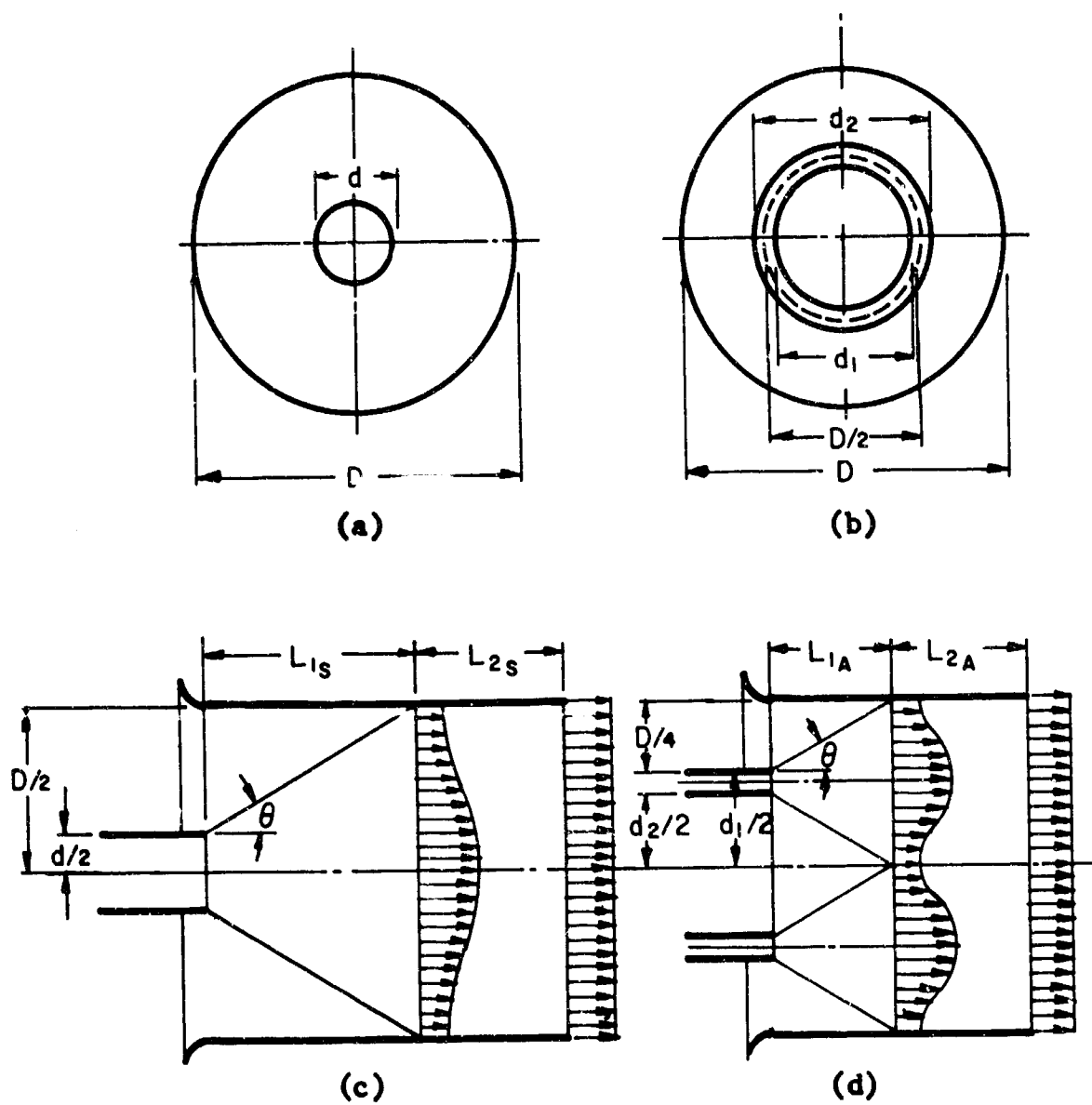
Figure 4. Definition of Parameters for
Single and Annular Nozzle Configurations.

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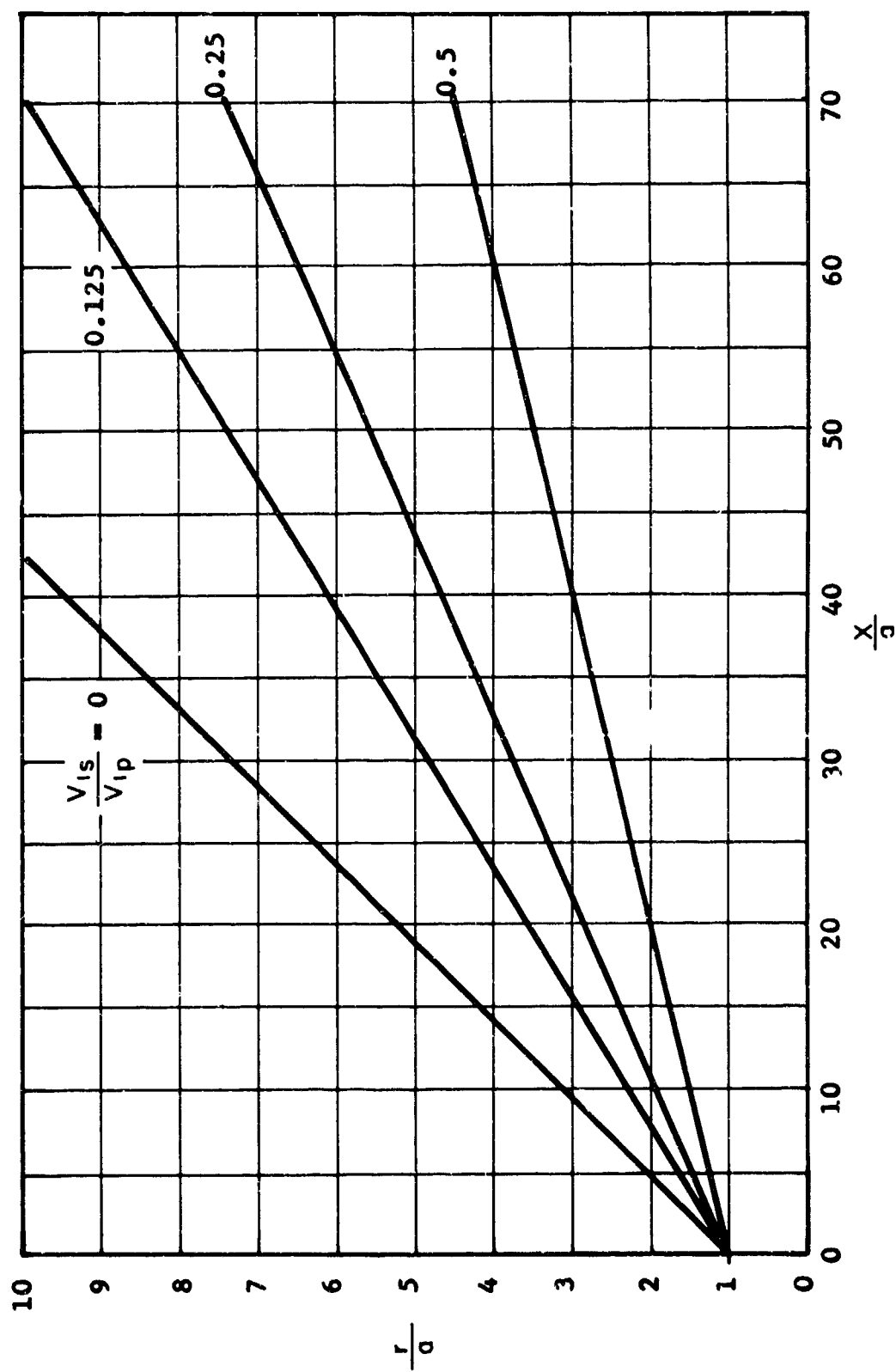
Figure 5. Jet Boundaries.

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streamwise distance from the primary jet exit is denoted by X, and the radial distance of the jet boundary from the jet center line is denoted by r. Typical variations of V_{IS}/V_{Ip} versus secondary-to-primary area ratio α_E are shown in Figure 6.

Using Figures 5 and 6, the length L_I can now be determined as follows:

(i)   A value α_E is assumed, and from Figure 6 the corresponding value of V_{IS}/V_{Ip} is obtained.

(ii)   The value of r/a is obtained from the following relationship:

$$r/a = \sqrt{\alpha_E + I} \tag{116}$$

(iii)   With the above values of V_{IS}/V_{Ip} and r/a, the corresponding value of X/a is obtained from Figure 5.

(iv)   Finally,

$$\frac{L_I}{D} = \frac{1}{2}\left(\frac{X/a}{r/a}\right) \tag{117}$$

The above calculations were repeated for several values of α_E, and the results are plotted in Figure 7 for the incompressible and the compressible analyses. Similar curves can also be obtained including various flow losses. Figure 7 indicates that, for practical values of α_E, the ratio (L_I/D) is of the order of 3 to 4.

Insufficient data exist to determine the length of the second part of the mixing chamber, L_2. However, it will be assumed that this length is

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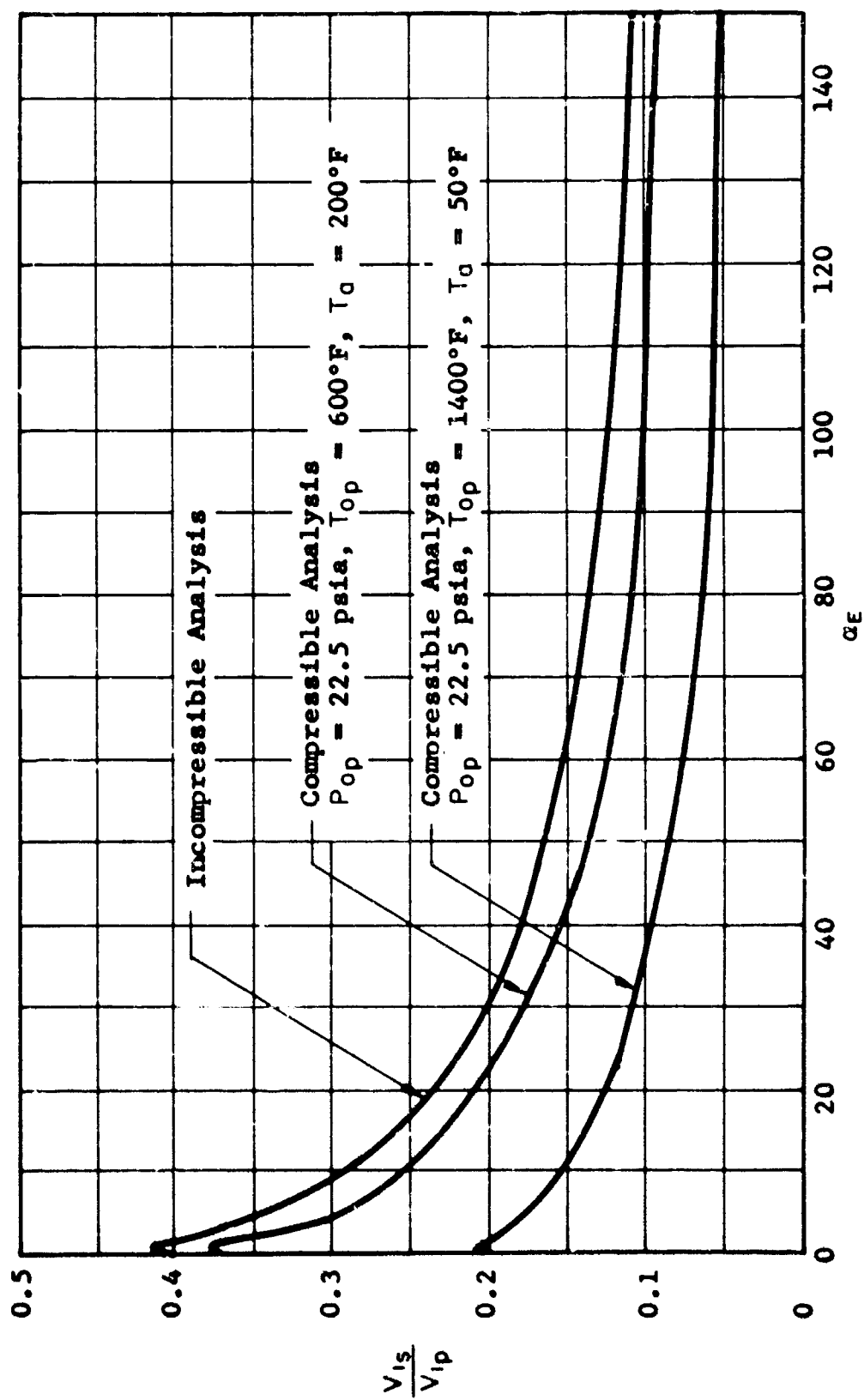
Figure 6. Variation of Secondary-to-Primary Velocity Ratio with Secondary-to-Primary Area Ratio (No Diffuser; No Forward Speed; No Losses).

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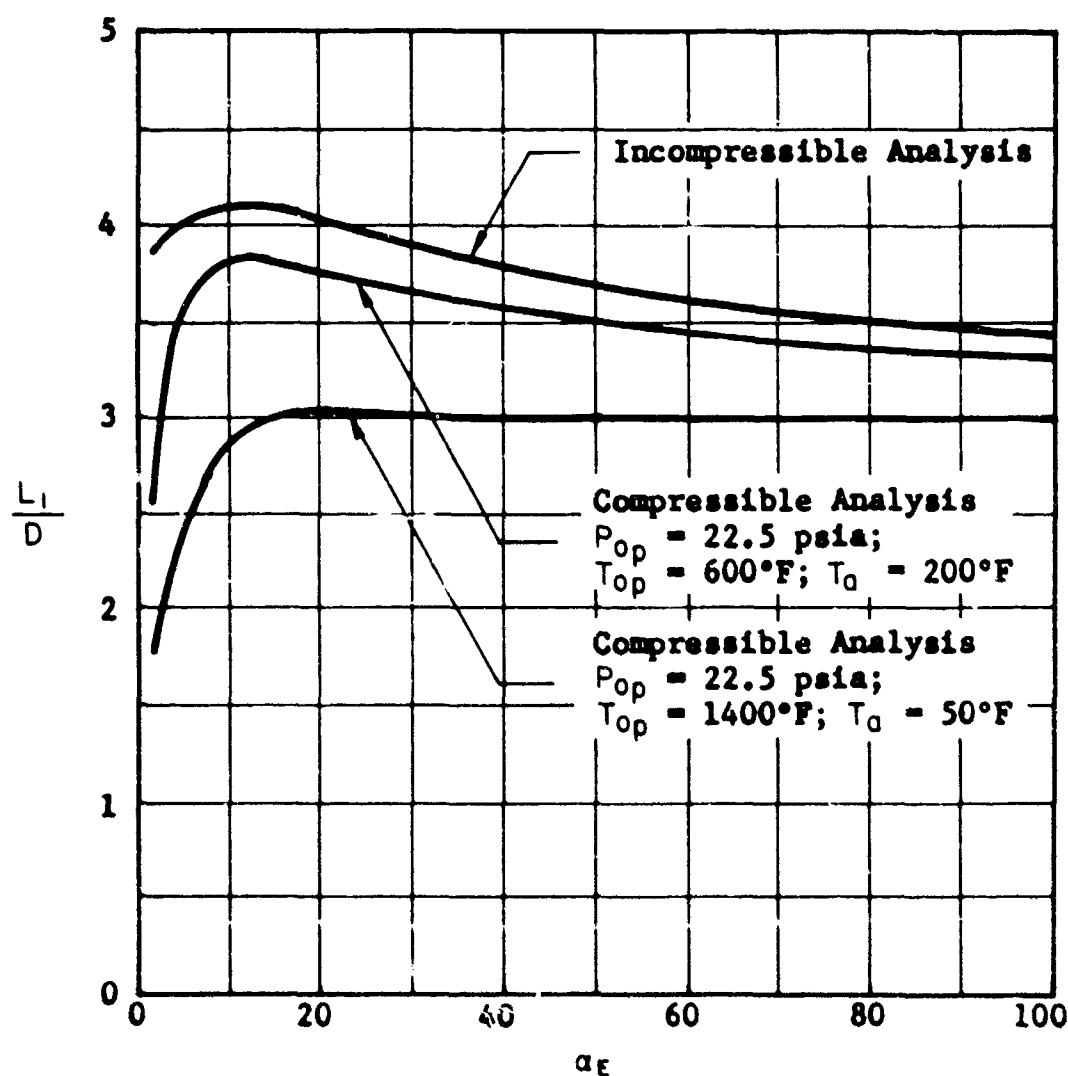
Figure 7. Variation of Length of the First Part
of Mixing Chamber with Secondary-to-Primary
Area Ratio (No Diffuser; No Forward Speed;
No Losses).

proportional to the contact surface area between the primary and the surrounding flows.

b. **Multiple Nozzle Configuration**

The first portion of the mixing chamber length, L_1, for a multiple nozzle configuration can easily be determined for the two-dimensional ejector by assuming that these nozzles are evenly spaced with respect to the mixing chamber and with respect to each other.

For a multiple nozzle configuration having N number of nozzles of the same total area as the single central nozzle, $(A_{1p})_s$, the primary area of each nozzle is

$$(A_{1p})_M = \frac{1}{N}(A_{1p})_s \qquad (118)$$

Also, if the total secondary area of the multiple and single nozzle configurations is the same, it follows that

$$(A_{1s})_M = \frac{1}{N}(A_{1s})_s \qquad (119)$$

Therefore, from equations (118) and (119) it follows that the secondary-to-primary area ratio for each nozzle of multiple nozzle configuration is the same as that for the corresponding single central nozzle type, i.e.,

$$(\alpha_E)_M = \frac{(A_{1s})_M}{(A_{1p})_M} = \frac{(A_{1s})_s}{(A_{1p})_s} = (\alpha_E)_s \qquad (120)$$

Since the area ratios are the same (equation 120), using Figure 7, the effective (L_1/D) for each nozzle of the multiple nozzle configuration is the same as that for the single nozzle design, i.e.,

$$\left(\frac{L_1}{D}\right)_M = \left(\frac{L_1}{D}\right)_S \tag{121}$$

From equation (119), the diameter of the effective mixing chamber for each nozzle of the multiple nozzle configuration can be determined as follows:

$$\left(\frac{\pi D}{4}\right)^2_M = \frac{1}{N}\left(\frac{\pi D}{4}\right)^2_S \tag{122}$$

or

$$(D)_M = \frac{1}{\sqrt{N}}(D)_S \tag{123}$$

From equations (121) and (123), it follows that the mixing chamber length (L_1) required for the jet boundary to reach the ejector walls for the multiple nozzle configuration is reduced by a factor of $1/\sqrt{N}$ of the corresponding single nozzle length. Thus,

$$(L_1)_M = \frac{1}{\sqrt{N}}(L_1)_S \tag{124}$$

Assuming that the second part of the mixing chamber length L_2 is a function of the total contact area of the primary flow with the surrounding air, the relationship for the mixing chamber lengths $(L_2)_M$ and $(L_2)_S$ of multiple and single nozzle configurations can be obtained as follows:

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The contact area of the primary jet with the
surrounding flow for a single central nozzle type
is given by

$$(S)_S = \pi (D)_S (L_2)_S \tag{125}$$

Similarly, the total contact area of the primary
jet for a multiple nozzle configuration of N
nozzles is

$$(S)_M = N \pi (D)_M (L_2)_M \tag{126}$$

Substituting equation (123) into (126) yields

$$(S)_M = \sqrt{N} \, \pi (D)_S (L_2)_M \tag{127}$$

Assuming that in each case the contact areas are
such as to produce complete mixing at the exit of
the mixing chamber, equations (125) and (127) yield

$$(L_2)_M = \frac{1}{\sqrt{N}} (L_2)_S \tag{128}$$

Combining equations (124) and (128), there follows

$$(L)_M = \frac{1}{\sqrt{N}} (L)_S \tag{129}$$

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Equations (124), (128), and (129) indicate that for a multiple nozzle jet ejector configuration, each part of the mixing chamber length as well as the total length reduces by a factor of $1/\sqrt{N}$ as compared with the single central nozzle configuration. This reduction in the mixing chamber length results in the reduction of head loss due to wall friction. Therefore, the multiple nozzle configuration would yield a superior performance as compared to that of the equivalent single nozzle ejector if the complete mixing conditions at the exit of the mixing chamber are satisfied in each case.

c. Annular Nozzle Configuration

For the case of an annular primary jet located midway between the walls and the center of the mixing chamber walls, both parts of the mixing chamber lengths $(L_1)_A$ and $(L_2)_A$, as discussed above, will also substantially reduce as compared to the equivalent single nozzle configuration.

The analysis for determining the mixing chamber lengths for the annular nozzle ejector can be performed as follows:

Using Figure 4(a), the primary area of the single nozzle configuration is given by

$$(A_{1p})_s = \frac{\pi}{4} d^2 \qquad (130)$$

From Figure 4(b), the corresponding primary area for the annular nozzle is

$$(A_{1p})_A = \frac{\pi}{4}(d_2^2 - d_1^2) \qquad (131)$$

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For the same primary jet areas, equations (130) and (131) yield

$$d^2 = d_2^2 - d_1^2 = (d_2 + d_1)(d_2 - d_1) \qquad (132)$$

Since the annular jet is centrally located within the mixing chamber having a fixed diameter D, it follows that

$$\frac{d_2 + d_1}{2} = \frac{D}{2} \qquad (133)$$

Equations (132) and (133) yield

$$d_2 - d_1 = \frac{d^2}{D} \qquad (134)$$

Since the primary jet areas for the two configurations are the same and since outside diameters D of the mixing chambers are also the same, it follows that

$$(A_{1_S})_S = (A_{1_S})_A = \frac{\pi}{4}(D^2 - d^2) \qquad (135)$$

From the above analysis it therefore follows, that the secondary-to-primary area ratio of the annular nozzle ejector is equal to that of the equivalent single central nozzle configuration, i.e.,

$$(\alpha_E)_A = (\alpha_E)_S$$

Using equations (130) and (135), the corresponding secondary-to-primary area ratios are

$$\alpha_E = \frac{A_{is}}{A_{ip}} = \frac{D^2}{d^2} - 1 \qquad (136)$$

$$\therefore \quad \frac{D}{d} = \sqrt{\alpha_E + 1} \qquad (137)$$

Assuming identical primary jet stagnation conditions, the velocity ratios V_{is}/V_{o} will also be equal. Using Figure 5, it therefore follows that the primary jet expansion angle,

$$\theta = \tan^{-1}\left(\frac{r/a}{X/a}\right) \quad ,$$

for annular nozzle configuration and the corresponding single jet will be the same. Thus, using Figure 4(c), the first part of the mixing chamber length for a single nozzle configuration can be expressed as follows:

$$(L_1)_S = \frac{D - d}{2} \cdot \frac{1}{\tan\theta} \qquad (138)$$

Similarly, using Figure 4(d), the corresponding length for the annular nozzle ejector is

$$(L_1)_A = \frac{D - (d_2 - d_1)}{4} \cdot \frac{1}{\tan\theta} \qquad (139)$$

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Equations (138) and (139) yield

$$\frac{(L_1)_A}{(L_1)_S} = \frac{1}{2}\left[\frac{D-(d_2-d_1)}{D-d}\right] \qquad (140)$$

Substituting equation (134) into equation (140), there follows

$$\frac{(L_1)_A}{(L_1)_S} = \frac{1}{2}\left(1+\frac{d}{D}\right) \qquad (141)$$

Substituting equation (137) into (141) yields

$$\frac{(L_1)_A}{(L_1)_S} = \frac{1}{2}\left(1+\frac{1}{\sqrt{\alpha_E}+1}\right) \qquad (142)$$

or

$$(L_1)_A = \frac{1}{2}\left(1+\frac{1}{\sqrt{\alpha_E}+1}\right)(L_1)_S \qquad (143)$$

Equation (143) shows that the first part of the mixing length $(L_1)_A$ for the annular nozzle configuration is a function of the area ratio α_E and that for large values of α_E it is approximately equal to a half that of the corresponding single central nozzle ejector. For small values of the area ratios, this length approaches $(L_1)_S$.

The second part of the mixing chamber length for the annular nozzle ejector can be determined as follows:

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The surface contact area of the primary jet with
the surrounding flow for a single nozzle ejector is

$$(S)_S = \pi d (L_2)_S \qquad (144)$$

The corresponding contact area for the annular jet
is given by

$$(S)_A = \pi (d_2 + d_1)(L_2)_A \qquad (145)$$

Assuming that in each case the same constant contact
surface area is required to complete the mixing
process at the exit of the mixing chamber,
equations (144) and (145) yield

$$(L_2)_A = \frac{d}{d_2 + d_1} (L_2)_S \qquad (146)$$

Substituting equation (143) into (146) yields

$$(L_2)_A = \frac{d}{D} (L_2)_S \qquad (147)$$

From equations (142) and (147), there results

$$(L_2)_A = \frac{1}{\sqrt{\alpha_E + 1}} (L_2)_S \qquad (148)$$

Equation (148) shows that the second part of the
mixing chamber length for the annular nozzle
configuration reduces by a factor of $1/\sqrt{\alpha_E + 1}$
as compared to that of the equivalent single jet
ejector.

Finally, using equations (143) and (148), the
total mixing length for the annular jet ejector
is given by

$$(L)_A = \frac{1}{2}\left(1 + \frac{1}{\sqrt{\alpha_E + 1}}\right)(L_1)_s + \frac{1}{\sqrt{\alpha_E + 1}}(L_2)_s \qquad (149)$$

V.   EFFECT OF PARAMETERS ON JET EJECTOR PERFORMANCE

Presented in this section are the results of a study showing
the effects of various aerodynamic, thermodynamic, and
geometric flow parameters on ejector thrust augmentation
performance.   The study includes the following parameters:

A.   FLOW LOSSES

The effect of flow losses is to reduce ejector performance.
This effect can be clearly seen from the nomographs of
Section VII and requires no further explanation.

B.   DIFFUSER

The results of the idealized analysis presented in Figures 8
and 9 show that under static conditions, at any secondary-to-
primary area ratio, an increase in diffuser area ratio yields
better thrust augmentation performance. However, as shown in
Figure 10, this is not true for a practical case when the
flow losses are included. Although the overall diffuser loss
factor λ_D varies with the area ratio α_D, for the purpose of
this discussion all flow losses including the diffuser loss
factor λ_D are held constant (at typical values) for all
diffuser area ratios.

Examining Figure 10, it can be seen that for any practical
value of secondary-to-primary area ratio α_E, the thrust
augmentation ratio ϕ reaches an optimum value with the
diffuser area ratio α_D ranging between 1.5 and 2.0. For the
diffuser area ratios larger than 2.0, the thrust augmentation
ratio would be actually lower than that indicated in
Figure 10 as a result of increase in the diffuser loss factor
λ_D with increase of α_D.

C.   FORWARD SPEED

Figure 11 shows the effect of forward speed on thrust
augmentation ratio for an idealized condition with no flow
losses and no diffuser. It can be seen from this figure
that an increase in forward speed results in a substantial
reduction of thrust augmentation ratio for all secondary-to-
primary area ratios, α_E. Furthermore, for any specific
nonzero value of forward speed, the thrust augmentation
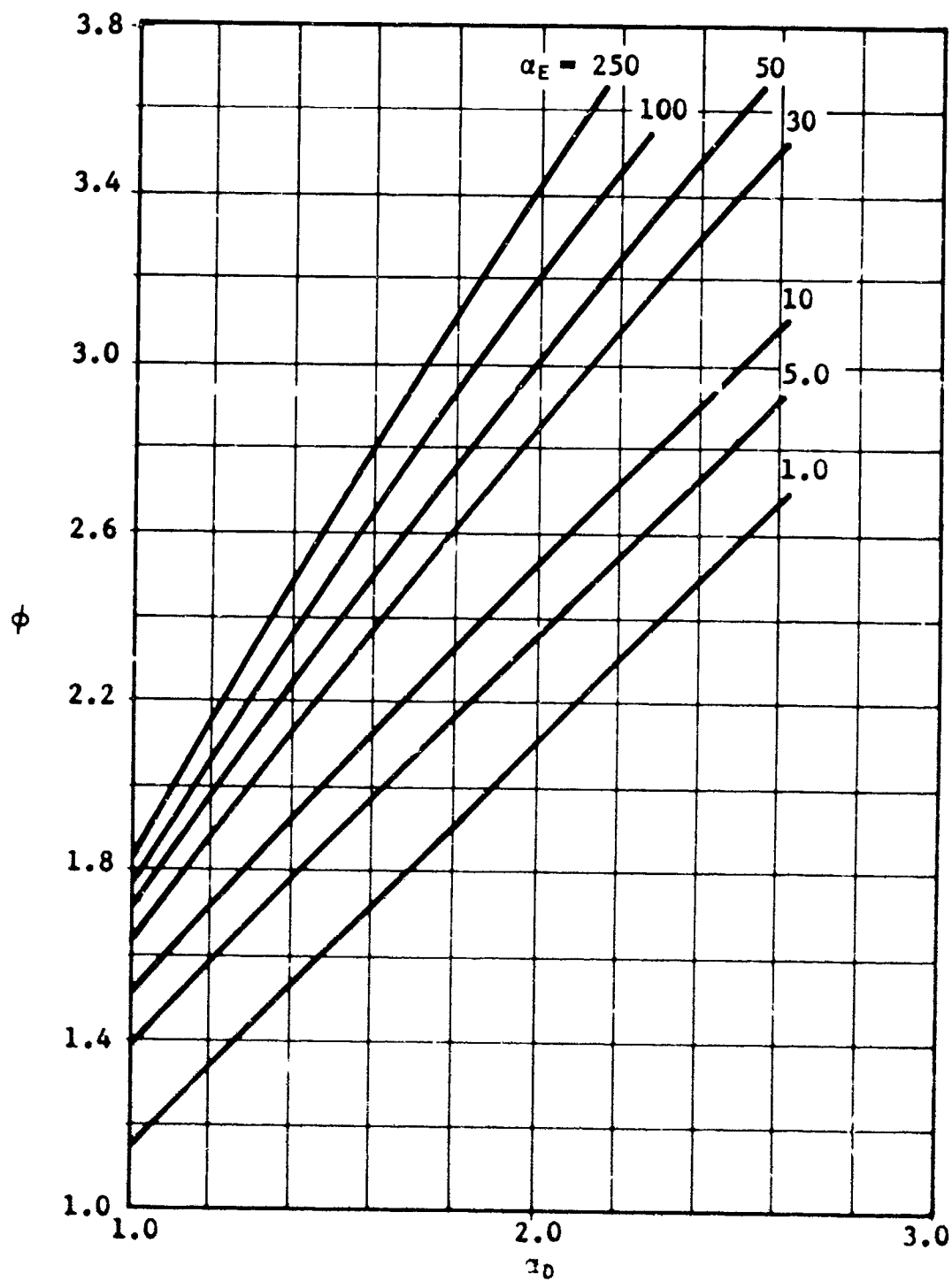
Figure 8. Effect of Diffuser on Thrust Augmentation of a Jet Ejector with Constant Area Mixing Chamber (No Forward Speed, No Flow Losses).
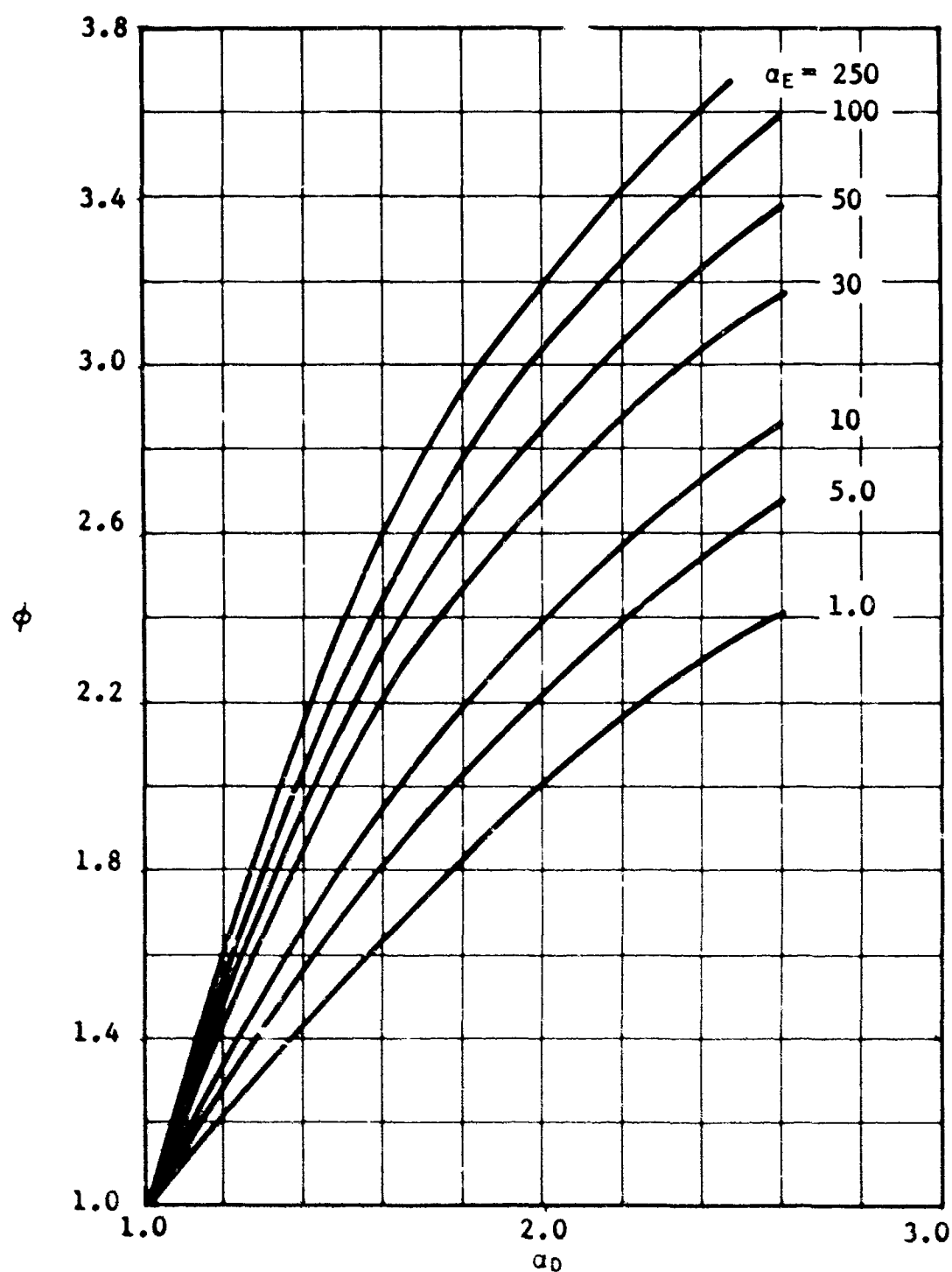
Figure 9. Effect of Diffuser on Thrust Augmentation of a Jet Ejector with Constant Pressure Mixing Chamber (No Forward Speed, No Flow Losses).
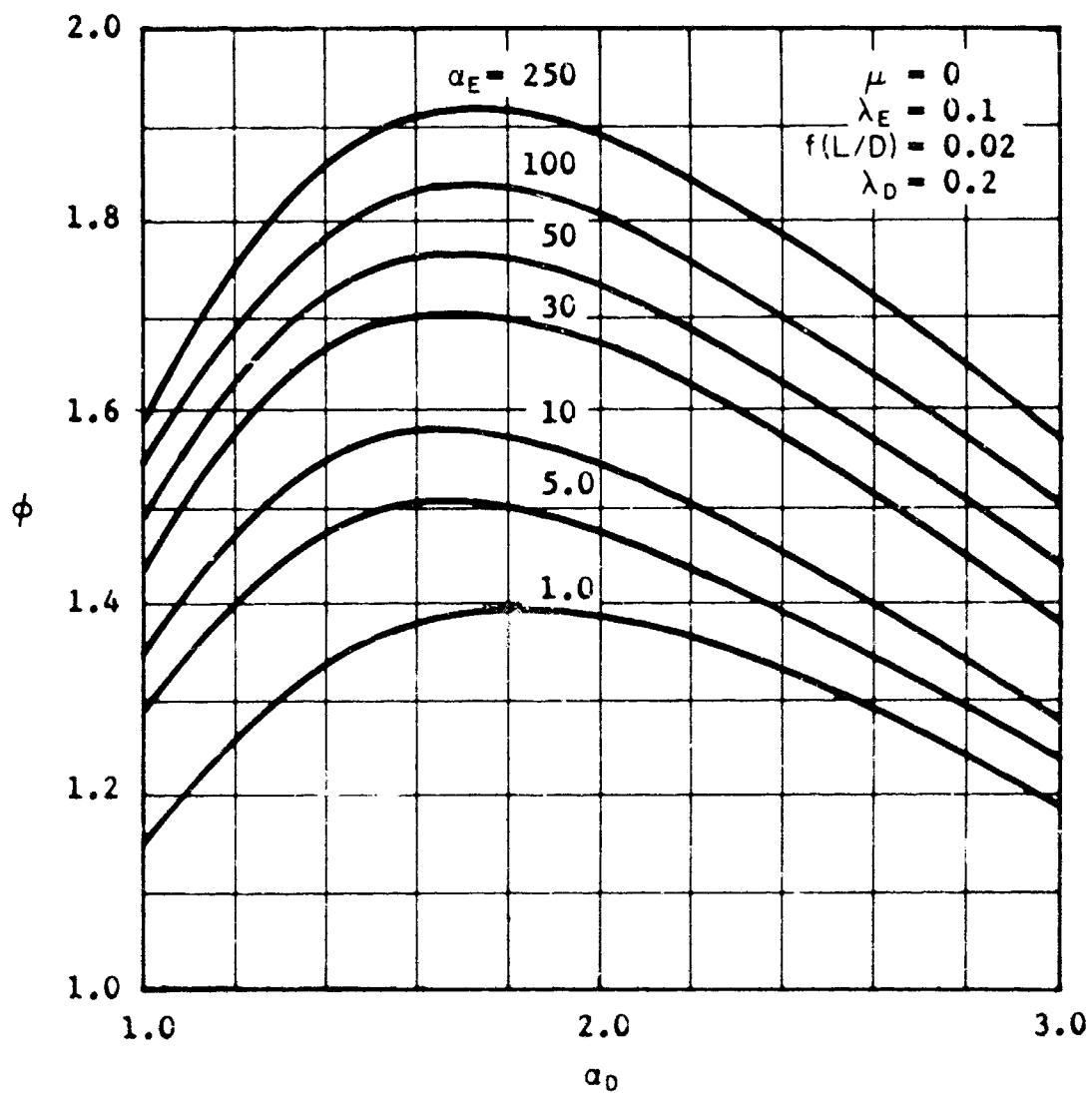
Figure 10. Effect of Diffuser on Thrust Augmentation of a Jet Ejector with Constant Area Mixing Chamber (No Forward Speed, With Typical Flow Losses).

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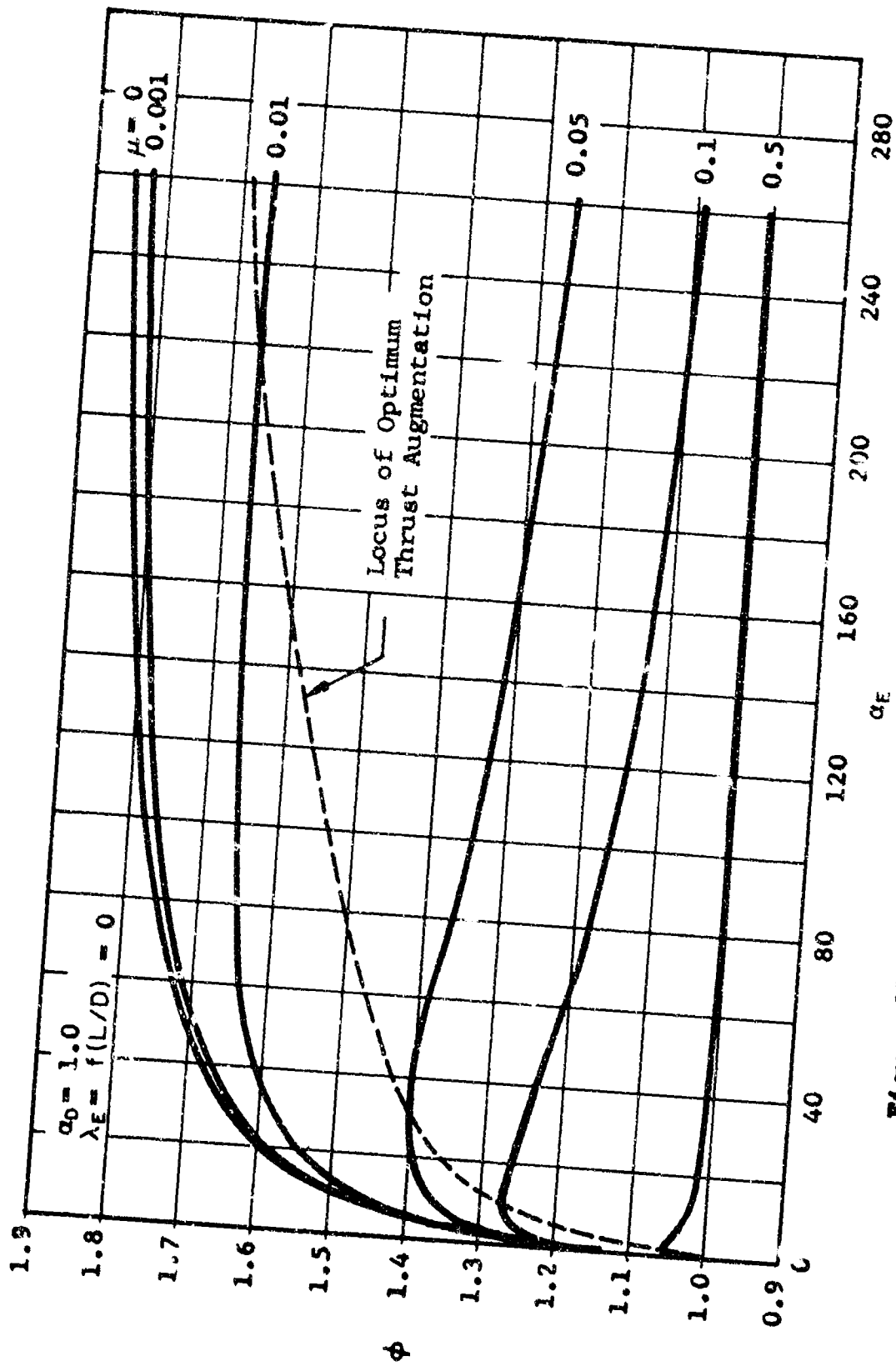
Figure 11. Effect of Forward Speed on Thrust Augmentation Ratio (No Diffuser; No Losses).

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ratio reaches an optimum value of $1.0 < \phi < 2.0$, and then reduces to unity as the area ratio further increases to infinity. From a physical point of view, the case of infinite α_E corresponds to the condition of primary flow discharged directly into the ambient, resulting in thrust augmentation ratio of unity. This figure also shows the locus of maximum thrust augmentation ratio (dotted line) as a function of α_E for the range of forward speed considered.

Figure 12 shows the effect of forward speed on thrust augmentation ratio ϕ, including typical flow losses for the case of $\alpha_D = 2.0$. Comparing Figures 11 and 12, it can be noted that the effect of forward speed on the reduction of thrust augmentation ratio is more severe when the major flow losses are included. Specifically, for forward speeds greater than $\mu = 0.05$, the thrust augmentation ratio continuously reduces with an increase in α_E and eventually reaches a value of less than 1.0 in the practical design range of α_E.

The above discussion refers to an ejector forward speed along the ejector longitudinal axis, i.e., parallel to jet thrust. If, however, the forward motion is normal to the ejector axis, under idealized flow condition, the ejector performance should not be affected by such motion. In a practical case, the forward motion of an ejector perpendicular to the direction of thrust will result in an asymmetric inflow at the secondary entrance, thereby causing an increase in the secondary entrance head loss $\rangle_{\_}$.

D. FLOW COMPRESSIBILITY

The effect of flow compressibility on jet ejector performance is herein determined assuming no forward speed, no diffuser, and no flow losses. Typical computer results for this analysis are presented in Figures 13 through 15. In each of these figures, the thrust augmentation ratio obtained from the idealized incompressible analysis is also shown for the purpose of comparison. It is seen that in general the thrust augmentation ratio ϕ is reduced when the flow compressibility is accounted for.

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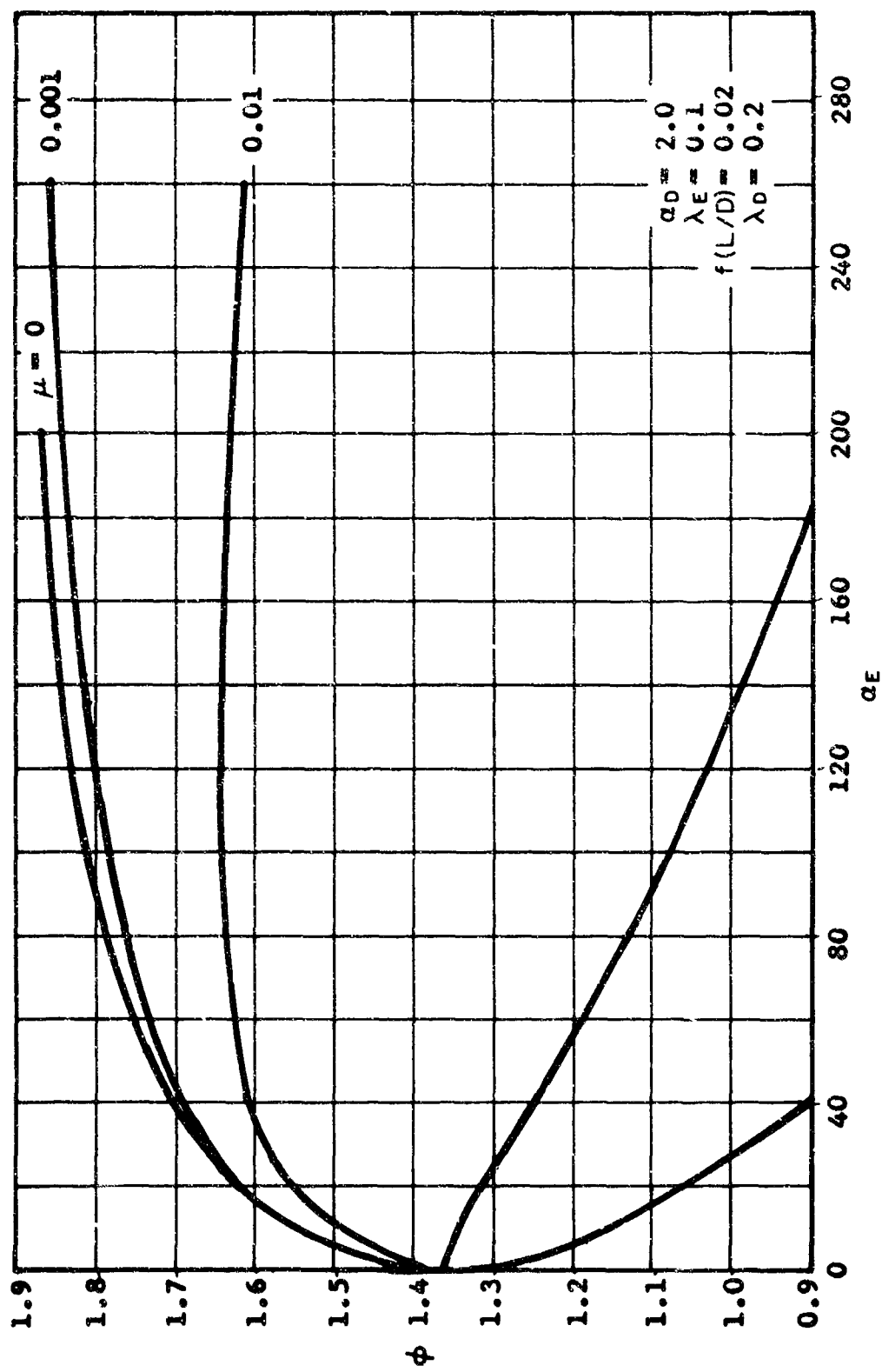
Figure 12. Effect of Forward Speed on Thrust Augmentation Ratio (with Diffuser; with Typical Losses).

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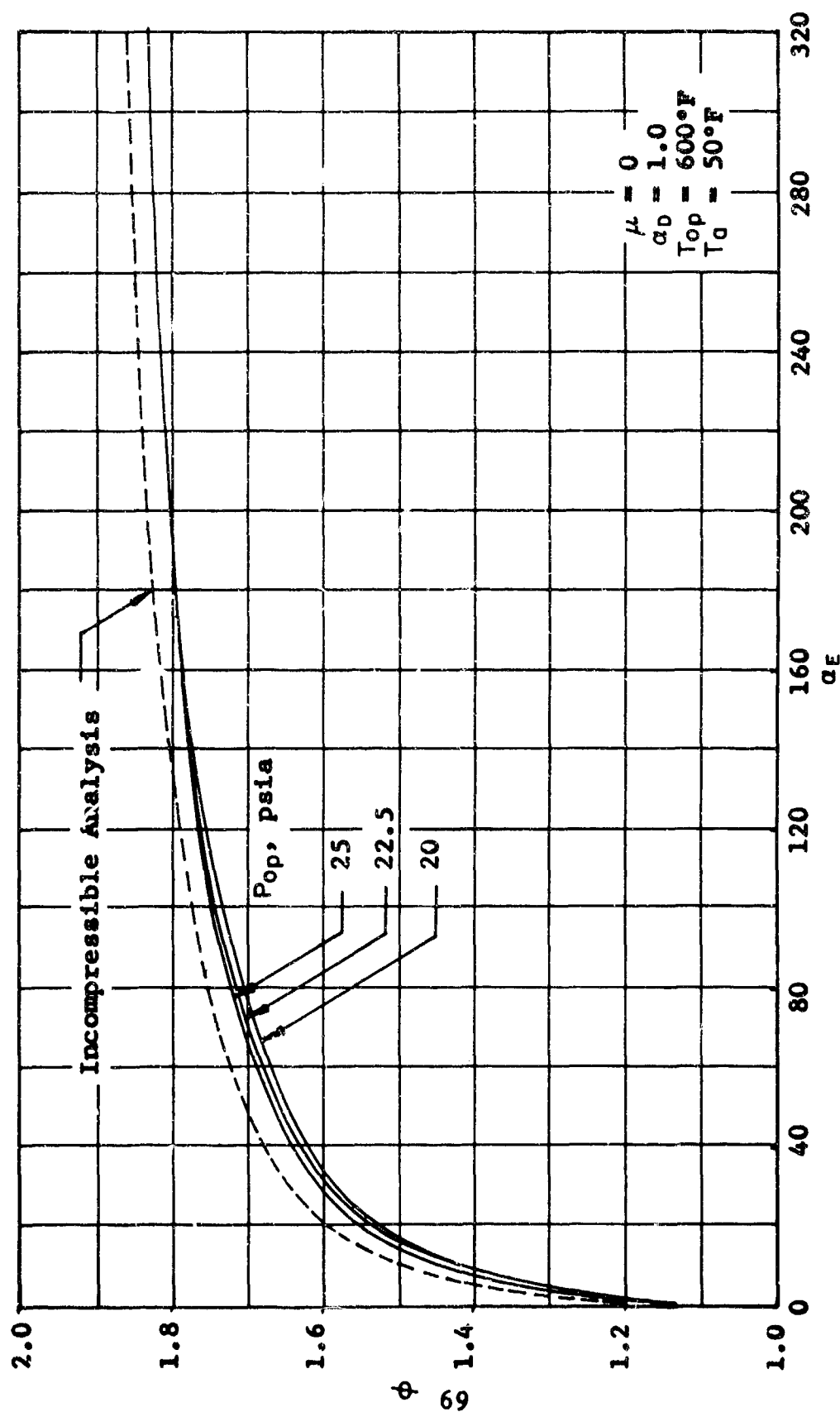
Figure 13. Effect of Primary Stagnation Pressure on Thrust Augmentation Ratio (No Forward Speed; No Diffuser; No Losses).
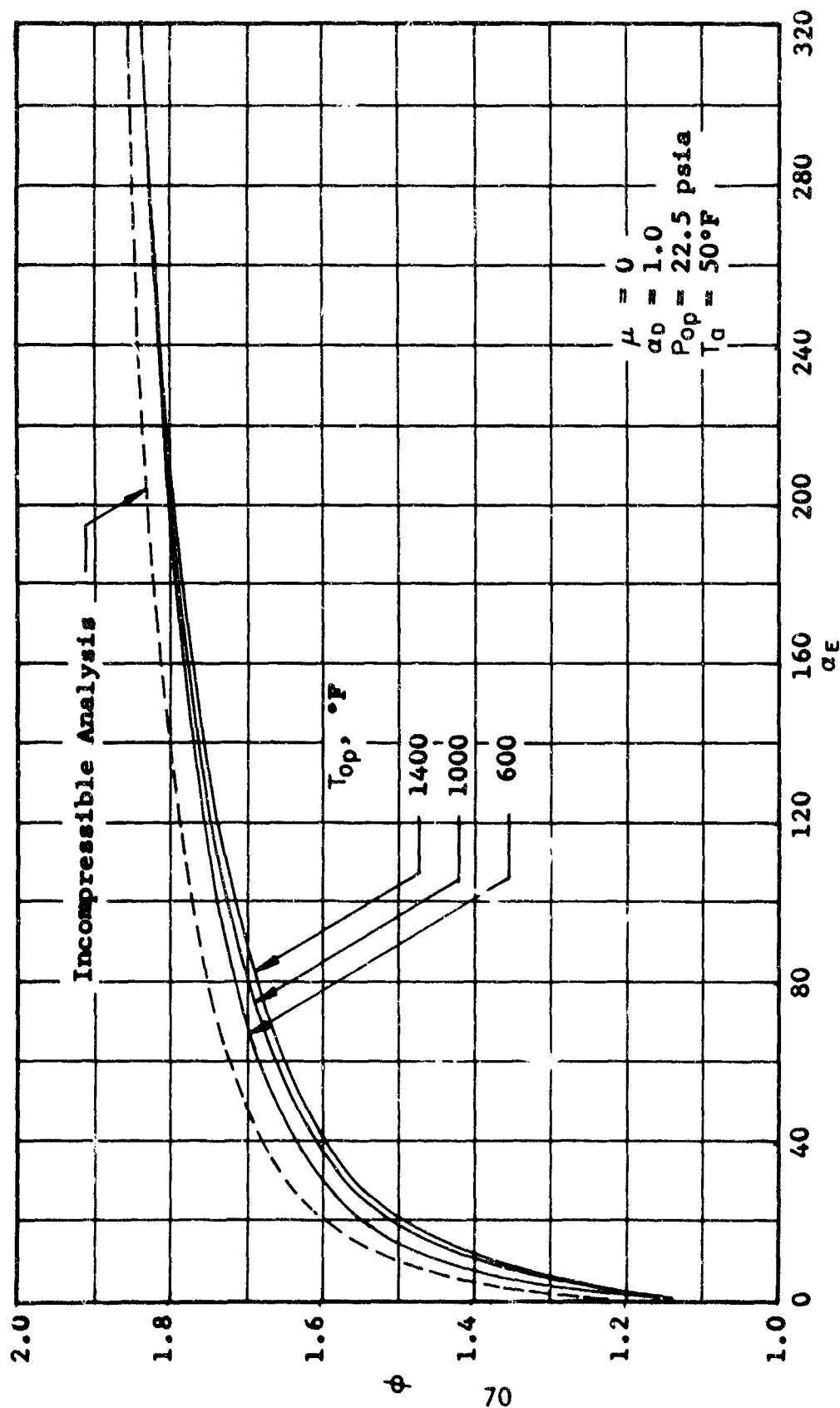
Figure 14. Effect of Primary Stagnation Temperature on Thrust Augmentation Ratio (No Forward Speed; No Diffuser; No Losses).
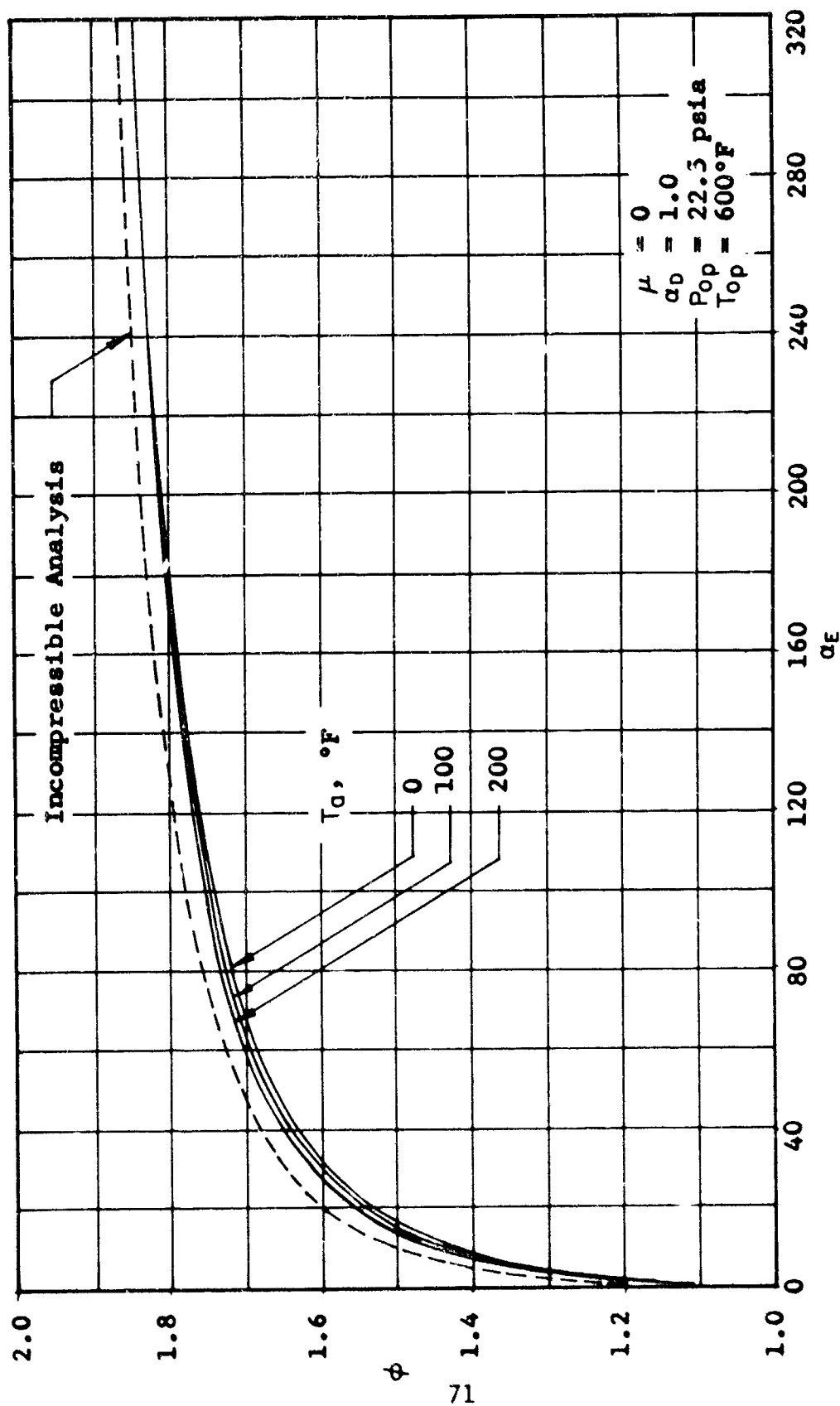
Figure 15. Effect of Ambient Temperature on Thrust Augmentation Ratio (No Forward Speed; No Diffuser; No Losses).

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Figure 13 shows that the increase of the primary stagnation pressure P_{Op} from 20 psia to 25 psia results in about 3 percent reduction of the thrust augmentation ratio. P_{Op} is limited to 25 psia in the calculations in order to avoid the choking condition of the nozzle.

The effect of the variation of the primary stagnation temperature T_{Op} is illustrated in Figure 14. The temperature range under consideration is between 600°F and 1400°F. It is seen from this figure that an increase of temperature T_{Op} decreases the thrust augmentation ratio up to a maximum of about 4 percent at area ratios around 10.

The increase in ambient temperature, as shown in Figure 15, results in an increase of thrust augmentation ratio ϕ. This increase, however, does not exceed 2 percent for the range of ambient temperatures raised from 0°F to 200°F and the range of α_E considered.

In general, it can be concluded that although the effect of flow compressibility is to reduce the jet ejector performance as compared to the idealized flow conditions, the effect of the variation of the compressible flow parameters, such as P_{Op}, T_{Op}, and T_a, seems to be of little consequence.

E. MIXING CHAMBER SHAPE

In the present investigation, two mixing chamber shapes have been considered; i.e., the constant area and the constant pressure mixing configurations.

The analysis of the mixing chamber shapes, other than the two investigated, is indeed a very difficult task and has not been successfully attempted by any of the investigators in the past. It appears, however, that due to possible flow separation at the mixing chamber walls, a divergent mixing chamber shape would not be suitable.

Some of the information on the mixing chamber shapes can be obtained by comparing Figures 8 and 9. Examining these figures, it can be seen that for the same secondary-to-primary area ratio α_E and diffuser area ratio α_D, the constant area mixing chamber shape yields superior thrust augmentation performance as compared to that of a constant pressure mixing configuration.

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F. MIXING CHAMBER LENGTH

The data presented in this report are valid only for the case when the velocity of the mixed flows at the exit of the mixing chamber is uniform. This implies complete mixing of the primary and secondary flows which necessitates adequate mixing chamber length.

The exact mixing process inside a mixing chamber of an ejector is not yet clearly understood. Mikhail (Reference 20) made an attempt to solve the problem; however, the final equations are developed in terms of "mixing length parameters" which vary from case to case and have to be determined empirically.

The experimental data of Reference 15 show that for the mixing chamber length of $L/D = 12$, the velocity distribution at the exit of the mixing chamber is uniform. The value of $L/D = 12$ is not necessarily representative for a variety of jet ejector configurations, since this value will in general depend on the secondary-to-primary area ratio α_E and other geometric parameters.

On the other hand, the experimental data of Reference 2 indicate that an increase in the mixing chamber length beyond the value of $L/D = 5.0$ or 6.0 causes an adverse effect on the jet ejector performance. This implies that the flow losses due to partial mixing, associated with short mixing chamber lengths, are less predominant than the friction losses caused by increasing mixing chamber length to achieve complete mixing. It appears, therefore, that in selecting practical mixing chamber lengths the considerations of the flow losses due to partial mixing may be of secondary importance.

This subject is further discussed later in the text. Also, the charts for estimating mixing chamber lengths of various ejector configurations are presented in Section VII. These charts are based on the fact that the practical mixing chamber length required for optimum ejector performance is less than that required for complete flow mixing. Furthermore, it is assumed that the flow losses due to partial mixing can be neglected provided that the total mixing chamber length for a single nozzle jet ejector is greater than $L/D = 6.0$.

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G. DIVERGENCE AND INCLINATION OF NOZZLES

In the previous discussions, it was assumed that, irrespective of the ejector type, the orientation of the primary jet nozzles was along the longitudinal axis of the ejector.

For the case of the central nozzle or multinozzles installed at an angle with the ejector axis, or for the case of the annular nozzle with the jet diverging from the ejector axis, the one-dimensional analysis is considered to be inadequate in predicting the performance of such ejector configurations. The major effect will be the increase of mixing losses due to the flow interaction which is difficult to treat analytically.

In the multiconcentric annular nozzle configuration as developed by Bertin, Reference 10, the divergence of the nozzle seems to be of merit insofar as mixing is concerned. However, no analytical work, besides the usual one-dimensional approach, has been presented by Bertin for the purpose of analyzing the performance of jet ejectors with divergent multiconcentric annular nozzles.

H. EFFECT OF GROUND PROXIMITY

Available test data, e.g., References 21 and 22, indicate that in the ground proximity, the thrust augmentation of an ejector is reduced. This is attributed to the reduction of static pressure prevailing in the flow from the ejector exit. The test data also show that the ejectors operating in parallel, with a common baseplate, yield a higher thrust augmentation than the ejectors operating individually. This is due to the building up of pressure underneath the baseplate where a stagnation condition exists. This effect is similar to what prevails in the case of annular nozzles in ground proximity, for which some theoretical and experimental data are presented in References 23 and 24.

I. NONUNIFORM VELOCITY AT THE SECONDARY ENTRANCE

The practical analysis presented in Section IV as well as other analyses available from the existing literature, is performed with a one-dimensional flow approach. The necessary assumptions, among others, are that the velocities at the secondary entrance and also at the mixing chamber exit are

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uniform. In practical operations these idealized conditions do not always apply.

For small secondary-to-primary area ratios, the velocity at the secondary entrance is practically uniform. However, as the area ratio α_E increases, the secondary entrance velocity close to the mixing chamber walls becomes much lower than that close to the primary jet.

For very large area ratios (as α_E tends to infinity), the velocity of the secondary flow becomes zero at a finite radial distance from the primary jet. In fact, this condition corresponds to a free jet discharged directly into the ambient, in which case no thrust augmentation is possible. The available analyses, utilizing the assumption of uniform secondary flow velocity, result, however, in a thrust augmentation ratio of 2.0 as α_E tends to infinity.

In the previous section, an attempt is made to account for the radial variation of the local velocity at the secondary entrance. However, this analysis is based on a semi-empirical approach requiring furhter experimental verification.

J. INCOMPLETE MIXING

The effect of incomplete (partial) mixing of the primary and secondary flows at the exit of the mixing chamber has also been investigated. As discussed previously, the incomplete mixing will exist due to the insufficient length of the mixing chamber, thereby resulting in a nonuniform velocity profile at the exit of the mixing chamber.

The difficulties of analyzing partial mixing are in principle similar to those associated with nonuniform velocity at the secondary entrance discussed above. In this case, however, even if the velocity profile at the exit of the mixing chamber 's known or assumed, the corresponding variation of the static pressure distribution cannot be analytically determined.

Forstall and Shapiro (Reference 25) indicate that the velocity profile at the exit of the mixing chamber can be quite accurately represented by a cosine or three-halves

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power curve. However, information on the static pressure
distribution at the exit of the mixing chamber and the mass
flow rate of the partially mixed flow is not available.
Thus, in order to predict reliably the effects of the
incomplete (partial) mixing, an experimental investigation is
necessary to obtain the pertinent data on pressure and
velocity distributions at the exit of the mixing chamber.

K. MIXING LOSSES IN THE MIXING CHAMBER

The mixing losses in the mixing chamber cannot be considered
as an additional external force which could be readily
introduced in the momentum equation. One method of
accounting for the mixing losses is to assume a mixing
efficiency factor (η_M) in the flow momentum considerations.
However, there is no information available for determining
this mixing efficiency factor.

L. FLOW VISCOSITY

A real fluid flow is generally treated as an inviscid flow,
except that at the locations close to the walls a boundary
layer effect is taken into consideration. The flow viscosity
effects give rise to friction drag which in turn reduces the
jet ejector thrust. In the present investigation, the losses
due to the friction drag along the mixing chamber walls are
included in the friction factor f, which appears in the
momentum equation.

For the diffuser section, the losses due to friction drag and
flow separation are included in the diffuser loss factor λ_D .

M. HEAT CONDUCTION LOSSES

In the practical analysis (compressible flow), the heat
conduction losses will affect the energy equations presented
in Section IV. However, the information pertaining to the
rate of heat conduction which varies with ejector geometry,
conductivity of mixing chamber walls, and the operating
conditions of the ejector system is inadequate for reasonable
evaluation.

Furthermore, due to the heat conduction losses, the ejector flows become neither isentropic nor adiabatic, resulting in an additional difficulty in analyzing the flow process.

In general, however, the mixing chamber is usually not very long and the secondary flow is almost under ambient conditions, so that heat conduction losses, if any, through the mixing chamber and diffuser walls are not significant and can be neglected without materially affecting the accuracy of the analysis.

N. EFFECT OF SPECIFIC HEAT RATIO γ

Using the computer program, Appendix I, an investigation was performed to determine the effects of the specific heat ratio γ on jet ejector performance. It was found, however, that for a range of γ from 1.25 to 1.4, the thrust augmentation ratio is practically unchanged (less than 0.1 percent).

It appears, therefore, that the effect of the specific heat ratio can be neglected in the practical jet ejector analysis.

VI. CORRELATION WITH EXPERIMENTAL DATA

Available experimental data which are suitable for
correlation with the results of the present analysis are
rather limited. Those data which contain information on
thrust augmentation do not, in general, furnish sufficient
design and construction details which could be used to
determine the various flow loss factors. Consequently, for
some of the jet ejector configurations, these loss factors
were determined by using good engineering judgement.

Specifically, the friction loss factor $f(L/D)$ was determined
assuming $f = 0.003$ and using the test values of (L/D)
provided in most cases. Reference 26 was used to determine
the overall diffuser loss factor λ_0.

As pointed out previously, it is not easy to determine the
secondary entrance flow loss factor λ_E. It appears that the
intake geometries of the various ejector configurations
tested are of either round or bellmouth shape, for which,
according to the results of Reference 27, the entrance loss
factor is about 0.1. Thus, in the absence of better infor-
mation applicable to each specific configuration, λ_E has been
taken as 0.1 for the present correlation.

The correlation of the test data with the theoretically
predicted results utilizing the loss factors described above
is performed in tabular form as shown below. The reason for
the selection of this method of presentation is the fact that
the test data obtained for a variety of jet ejector configura-
tions are unsuitable for graphical comparison.

The correlations are performed for the following jet ejector
configurations:

A. SINGLE CENTRAL NOZZLE CONFIGURATIONS

The following references contain the test data obtained for a
single central nozzle configuration:

(i) Reference 2 presents the test data for the case of
an ejector without a diffuser. The correlation of
these data with theoretically predicted values is
given in Table I.

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TABLE I

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 2,
SINGLE NOZZLE EJECTOR WITH NO DIFFUSER

α_E	ϕ Theory	ϕ Test
6.0	1.30	1.25
11.0	1.36	1.29
24.0	1.42	1.34
29.0	1.44	1.38
59.0	1.51	1.43

The calculated values are based on the following loss factors:

$$\lambda_E = 0.1$$

$$f(L/D) = 0.02$$

$$\lambda_D = 0 \text{ (No diffuser)}$$

The above table indicates a satisfactory correlation between the theoretical and experimental results.

(ii) The test data obtained from Reference 15 are for a central nozzle configuration without a diffuser. The correlation of the test results with the theoretically predicted values is given in Table II.

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TABLE II

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 15, SINGLE NOZZLE EJECTOR WITH NO DIFFUSER

α_E	ϕ Theory	ϕ Test
3.0	1.22	1.03
10.7	1.36	1.20
15.0	1.37	1.26
28.7	1.44	1.40
46.0	1.48	1.48
104.5	1.55	1.50

The theoretically predicted values are based on the following flow loss factors:

$$\lambda_E = 0.1$$

$$f(L/D) = 0.02$$

$$\lambda_D = 0 \text{ (No diffuser)}$$

The comparatively poorer correlation at small area ratios is believed to be due to the higher secondary entrance losses. Also, the test data indicate that with the increase of the area ratio α_E from 46.0 to 104.5 (more than double), the increase in augmentation ratio is only about 1 percent. On the other hand, from the theoretically predicted results, the corresponding increase in thrust augmentation is about 5 percent. This can be attributed to the effect of the nonuniform velocity profile at the secondary entrance (not accounted for in the theory). This effect becomes more important at high secondary-to-primary area ratios.

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(iii)   Reference 16 quotes the following test data for a
         constant area mixing ejector without diffuser:

α_E	Test
129.5	1.95
339.0	2.11
329.0	2.21
369.0	2.21

The thrust augmentation ratios shown above are
either close to or higher than the maximum possible
values which can be obtained from the idealized,
one-dimensional incompressible analysis, viz., 2.0.
Furthermore, on account of the large area ratios of
$\alpha_E >$ 130, the secondary velocity at the entrance
plane would no longer maintain its uniformity;
consequently, it would be doubtful whether the
maximum augmentation ratio of 2.0 could be reached
at all even if all the losses were neglected. The
original work (Reference 28) does not furnish any
usable information to justify the unusually high
performance claimed for the simple central nozzle
type ejector as illustrated therein.

(iv)   Reference 29 presents the test results for the
        ejector with and without a diffuser. The correla-
        tion of these data with the theoretically predicted
        values is given in Table III.

TABLE III

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 29,
SINGLE NOZZLE EJECTOR WITH AND WITHOUT DIFFUSER

α_E	α_D	ϕ Theory	ϕ Test
26.36	1.00	1.45	1.37
7.54	1.00	1.34	1.28
7.54	2.49	1.41	1.23
19.55	1.00	1.43	1.35
5.42	1.00	1.29	1.27
5.42	2.49	1.39	1.29

The test data of Table III indicate that for
constant area ratios (α_E = 7.54 or α_E = 5.42), the
addition of a diffuser with α_D = 2.49 results in a
reduction of thrust augmentation ratio ϕ . This
reflects a poor diffuser efficiency (high losses)
of the jet ejector configuration tested.

(v) The tests of Reference 30 were performed on a two-
dimensional model with no diffuser. A comparison
of the test data with the theoretically predicted
results is given in Table IV.

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TABLE IV

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 30,
SINGLE NOZZLE EJECTOR WITH NO DIFFUSER

α_E	ϕ Theory	ϕ Test
3.24	1.16	1.08
7.13	1.24	1.16
11.5	1.27	1.23
19.0	1.31	1.30
23.0	1.32	1.30
27.0	1.33	1.30
31.0	1.34	1.28

The predicted values are obtained by taking $\lambda_E = 0.1$ and $f(L/D) = 0.05$. A higher friction loss factor is used in this case, as compared with the above configurations, in view of the fact that due to the larger wall area in the two-dimensional model, the friction losses are undoubtedly higher, especially at low secondary-to-primary area ratios.

The results presented in Table IV show a good correlation between the theoretical and experimental values.

(vi) Reference 31 presents the test data on the effect of total primary stagnation pressure ratio on thrust augmentation. The test conditions are as follows:

$$T_{0_p} = 300°K = 510°R \ (50°F)$$

$$T_a = 283°K = 478°R \ (18°F)$$

$$\alpha_E = 50.0$$

$$L/D = 5.0$$

The test data of Reference 31 indicate that the thrust augmentation ratio ϕ decreases gradually from 1.24 to 1.22 as P_{0_p}/P_a increases from 1.4 to 1.8. From the analysis, the thrust augmentation ratio is obtained as 1.25 by taking $f(L/D) = 0.025$, as suggested by the paper.

(vii) Reference 32 shows that at an area ratio $\alpha_E = 2.33$, the central nozzle ejector without diffuser $(L/D = 6)$ has its thrust augmentation ratio ϕ decreasing from 1.195 to 1.165 as the primary pressure ratio P_{0_p}/P_a increases from 1.4 to 1.8. The corresponding theoretical value based on loss factors of $f(L/D) = 0.02$ and $\lambda_E = 0.1$ is 1.20.

B. MULTIPLE NOZZLE CONFIGURATIONS

The test data for the multiple nozzle configurations are obtained from the following references:

(i) The test data reported in Reference 13 pertain to an ejector configuration with multiple nozzles, a rectangular mixing chamber, and a diffuser with lemniscate contour. Table V shows the correlation of the test data with the theory.

TABLE V

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 13,
MULTIPLE NOZZLE EJECTOR WITH RECTANGULAR
MIXING CHAMBER AND A DIFFUSER

α_E	α_D	ϕ Theory	ϕ Test
35.5	3.11	1.38	1.55
55.5	2.73	1.54	1.66
74.4	2.36	1.70	1.79
135.5	1.36	1.79	1.78

The above table shows a satisfactory correlation between the test results and the corresponding theoretical values. This correlation is based on the following flow loss factors:

$$\lambda_E = 0.1$$

$$f(L/D) = 0.02$$

$$\lambda_D = 0.2$$

(ii) The test data of Reference 18 and the predicted values are given in Table VI.

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TABLE VI

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 18,
MULTIPLE NOZZLES ARRANGED IN A CIRCLE

α_E	α_D	ϕ Theory	ϕ Test
14.37	1.8	1.71	1.72
31.4	2.2	1.75	1.71
51.0	2.47	1.73	1.90

The test model used has multiple nozzles arranged in a circle. The mixing chamber is slightly convergent (the exit area is 8 percent less than the entrance area), which does not assu·e constant pressure at the walls. The predicted values shown in Table VI are obtained using the following loss factors:

$$\lambda_E = 0.1$$

$$f(L/D) = 0.01$$

$$\lambda_D = 0.2$$

It is seen that for the first two configurations, correlation is satisfactory, whereas for the last one the test result is 10 percent higher than that theoretically predicted.

(iii)   Table VII shows the effect of diffuser area ratio α_D on thrust augmentation ϕ for constant secondary-to-primary area ratio $\alpha_E = 12.0$. The test data were extracted from Reference 21 and are applicable to a four-row nozzle configuration.

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TABLE VII

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 21,
FOUR-ROW NOZZLE CONFIGURATION WITH VARIABLE DIFFUSER

α_E	α_D	ϕ Theory	ϕ Test
12.0	1.00	1.37	1.35
12.0	1.19	1.48	1.45
12.0	1.38	1.56	1.55
12.0	1.58	1.59	1.61
12.0	1.77	1.59	1.64
12.0	2.16	1.53	1.57

Table VII shows a good correlation between experimental and theoretical results, indicating that the best diffuser area ratio α_D for optimum thrust augmentation ratio is between $\alpha_D = 1.5$ and 2.0. Similar conclusion is reported in Section V, where the effects of a diffuser are discussed.

(iv) The configuration referred to in Reference 33 consists of a rectangular parallel-wall mixing chamber with a diffuser and multiple primary nozzles. The comparison of the predicted thrust augmentation ratios with the corresponding measured values is presented in Table VIII.

TABLE VIII

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 33, SINGLE AND THREE-ROW NOZZLES, RECTANGULAR MIXING CHAMBER WITH DIFFUSER

α_E	α_D	ϕ Theory	$\dfrac{\phi}{\text{Test}}$ Single-Row Nozzle	Three-Row Nozzle
6.6	1.23	1.44	1.27	1.36
12.0	1.38	1.56	1.37	1.50
29.3	1.61	1.70	1.45	1.83
51.0	1.73	1.77	1.56	1.89

The third column in Table VIII represents predicted values based on the following values of flow loss factors:

$$\lambda_E = 0.1$$

$$f(L/D) = 0.02$$

$$\lambda_D = 0.2$$

It is seen that for the first two area ratios ($\alpha_E = 6.6$ and 12.0), the predicted values are higher than the test data for both configurations, viz., single row of nozzles and three rows of nozzles. This is believed to be chiefly due to an underestimation of the total head loss factor at the secondary entrance λ_E.

For the other two area ratios ($\alpha_E = 29.3$ and 51.0), the predicted values are higher than the test data for the single-row nozzle configuration but lower than those for the three-row nozzle configuration.

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C. ANNULAR NOZZLE CONFIGURATIONS

Finally, for the annular nozzle configuration, the following test data are utilized:

(i) The tests as reported in Reference 22 were performed with single annular nozzle configurations. For the model with a straight mixing chamber (no diffuser), the results are shown in Table IX.

TABLE IX

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 22, ANNULAR NOZZLE EJECTOR WITH NO DIFFUSER

α_E	α_D	ϕ Theory	ϕ Test
13	1.0	1.41	1.29
17	1.0	1.44	1.38
22	1.0	1.46	1.42

The predicted values are based on the following flow losses:

$$\lambda_F = 0.1$$

$$f(L/D) = 0.01$$

$$\lambda_D = 0 \text{ (No diffuser)}$$

The corresponding results for a divergent mixing chamber-diffuser (exit area approximately double the entrance area) are shown in Table X.

TABLE X

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 22,
ANNULAR NOZZLE EJECTOR WITH DIVERGENT MIXING CHAMBER-DIFFUSER

α_E	ϕ Theory	ϕ Test
8	1.78	1.48
9	1.79	1.53
11	1.81	1.56

The theoretically predicted values for the thrust augmentation ratio ϕ have been obtained for a diffuser area ratio of $\alpha_D = 2.0$ with the following loss factors:

$$\lambda_E = 0.1$$

$$f(1/D) = 0 \text{ (No mixing chamber)}$$

$$\lambda_D = 0.2$$

The large discrepancy between the actual performance and the predicted results is attributed to the incomplete mixing that can be expected at the exit of a diverging mixing chamber-diffuser of relatively small length.

Presented in Reference 22 are also some two-dimensional and three-dimensional test results for the annular jet ejectors.

The correlation of theory with the two-dimensional results is shown in Table XI.

TABLE XI

CORRELATION OF THEORY WITH TWO-DIMENSIONAL DATA
OF REFERENCE 22, ANNULAR NOZZLE EJECTOR
WITH DIVERGENT MIXING CHAMBER-DIFFUSER

α_E	α_D	ϕ Theory	ϕ Test
9.0	2.0	1.80	1.30
11.5	2.0	1.82	1.50
14.0	2.0	1.84	1.43

The predicted values are obtained from the
practical analysis with the following flow loss
factors:

$$\lambda_E = 0.1$$

$$f(L/D) = 0 \text{ (No mixing chamber)}$$

$$\lambda_D = 0.2$$

As can be seen from Table XI, the test results are
appreciably lower than the corresponding predicted
values. This difference in the results can be
attributed to the following factors:

(a) The tests were performed for the ejector
configuration having a small length-to-
diameter ratio (L/D = 3.0). At this ratio
of L/D, it can be expected that the
mixing at the exit of the diffuser will
not be complete, contrary to the complete
mixing assumption in the theory.

(b) Since the primary jet is very close to the
diffuser walls, it is expected that the
friction loss in the diffuser will be
increased as compared to conventional

central nozzle configurations. This
increase in the skin friction in the
diffuser could be accounted for by
increasing the diffuser loss factor λ_D .

The correlation of three-dimensional test data of
Reference 22 with the theoretically predicted
results is shown in Table XII.

TABLE XII

CORRELATION OF THEORY WITH THREE-DIMENSIONAL DATA
OF REFERENCE 22, ANNULAR NOZZLE EJECTOR
WITH DIVERGENT MIXING CHAMBER-DIFFUSER

α_E	α_D	ϕ Theory	ϕ Test
20.8	1.45	1.66	1.34
20.8	1.63	1.69	1.40
20.8	1.85	1.68	1.47
20.8	1.94	1.66	1.49

The predicted results are based on the same loss
factors as the two-dimensional results. Also in
this correlation, the three-dimensional test data
are lower than the corresponding predicted values
for the same reasons as explained above in the
two-dimensional correlation.

(ii) Table XIII shows the correlation of the test data
as presented in Reference 34 with the theoretically
predicted values.

TABLE XIII

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 34,
THREE-RING ANNULAR NOZZLE EJECTOR WITH DIFFUSER

α_E	α_D	ϕ Theory	ϕ Test
44.0	1.58		1.93
44.0	1.90	2.02	2.16
44.0	2.30		2.32

The test data are for the configuration with a
three-ring annular nozzle. The theoretically
predicted value of ϕ = 2.02 applies to α_E = 44.0
and α_D = 2.0 and is based on the following loss
factors:

$$\lambda_E = 0.1$$

$$f(L/D) = 0 \text{ (No mixing chamber)}$$

$$\lambda_D = 0.2$$

It can be noted that the theoretically predicted
value is lower than the test data claimed.

VII. RAPID METHOD FOR EJECTOR PERFORMANCE PREDICTION

Presented in this section is a compilation of charts for
rapid prediction of jet ejector performance. The numerical
results used in these charts were obtained by solving the
theoretical flow equations presented in Section IV.

A. IDEALIZED ANALYSIS

The idealized flow equations were computed manually for both
constant area and constant pressure mixing. The corre-
sponding numerical results are herein presented in Figures
16 and 17, which show the variation of the idealized thrust
augmentation ratio ϕ as a function of secondary-to-primary
area ratio α_E for a series of constant values of diffuser
area ratio α_D.

B. PRACTICAL ANALYSIS

The practical analysis was solved with the aid of an IBM
360 digital computer utilizing FORTRAN IV machine language.
In this case, two computer programs were developed, one for
the incompressible analysis including the effects of major
flow losses, diffuser, and forward speed, and the other for
the compressible analysis including only the effects of flow
compressibility. A detailed description of the programs
including flow diagrams and typical computer outputs is
presented in Appendix I. The final computer results obtained
for static conditions are herein presented as nomographs,
Figures 18 through 22.

These charts represent an effective analytical tool in
predicting jet ejector performance including flow losses and
the effects of flow compressibility and are suitable for use
in the preliminary design of jet ejectors. One of the
advantages of the selected method of presentation is the
fact that a wide range of practical jet ejector operating
conditions as well as a variety of flow losses are condensed
in a total of five nomographs. Four of these charts,
Figures 18 through 21, contain the computer results for the

94
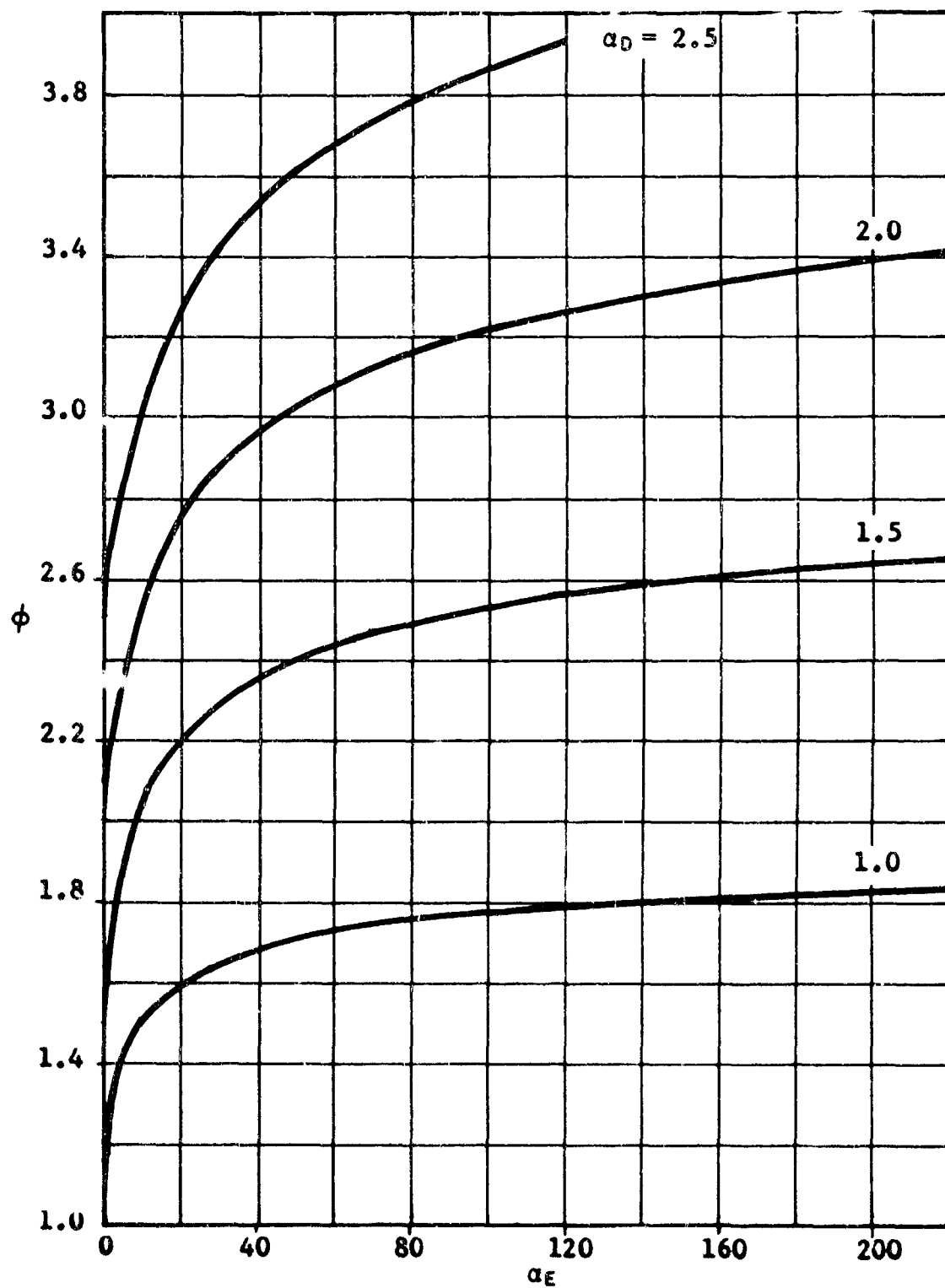
Figure 16. Thrust Augmentation Ratio -
Idealized Analysis for Constant Area
Mixing.
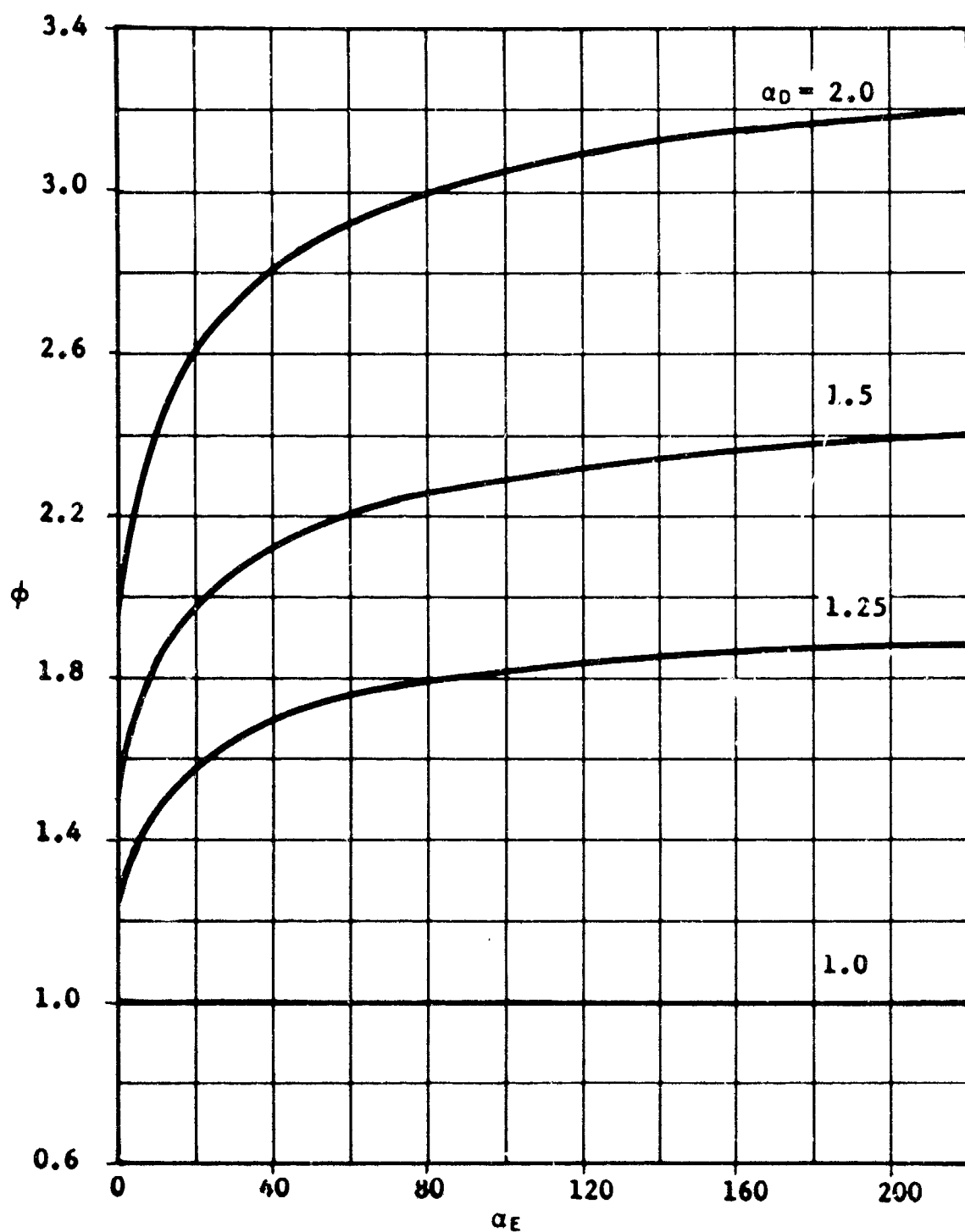
Figure 17. Thrust Augmentation Ratio -
Idealized Analysis for Constant Pressure
Mixing.

96
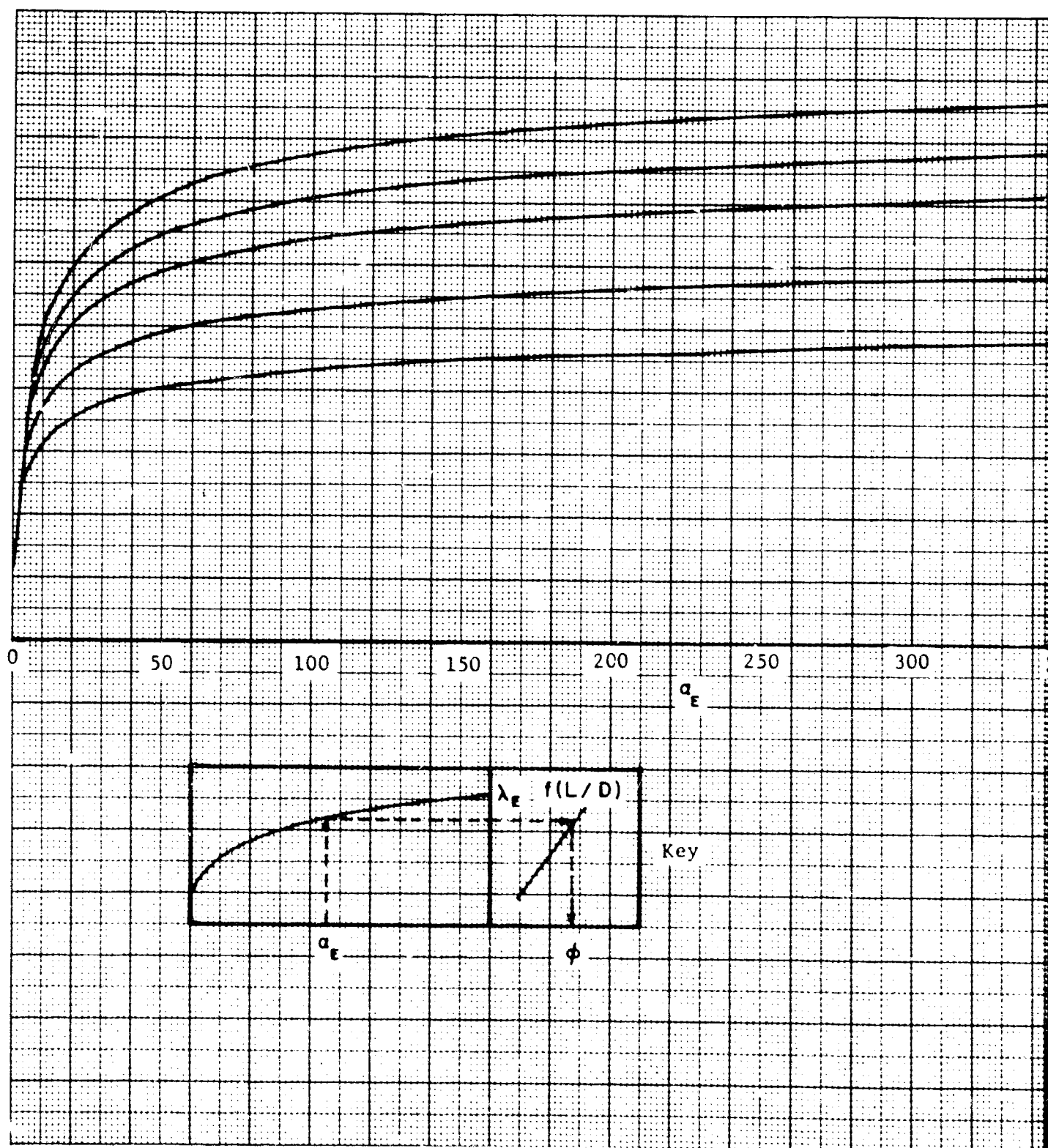
Figure 18. Nomograph for Thrust Augmentation Ratio - Incompressible Flow Analysis Including Flow Losses ($\alpha_0 = 1.0$; $\mu = 0$)

97

λ_E

0

0.05

0.1

0.2

0.3

f (L / D)

0.05

0.03

0.02

0.01

0

250   300   350   1.0   1.2   1.4   1.6   1.8   2.0

ϕ
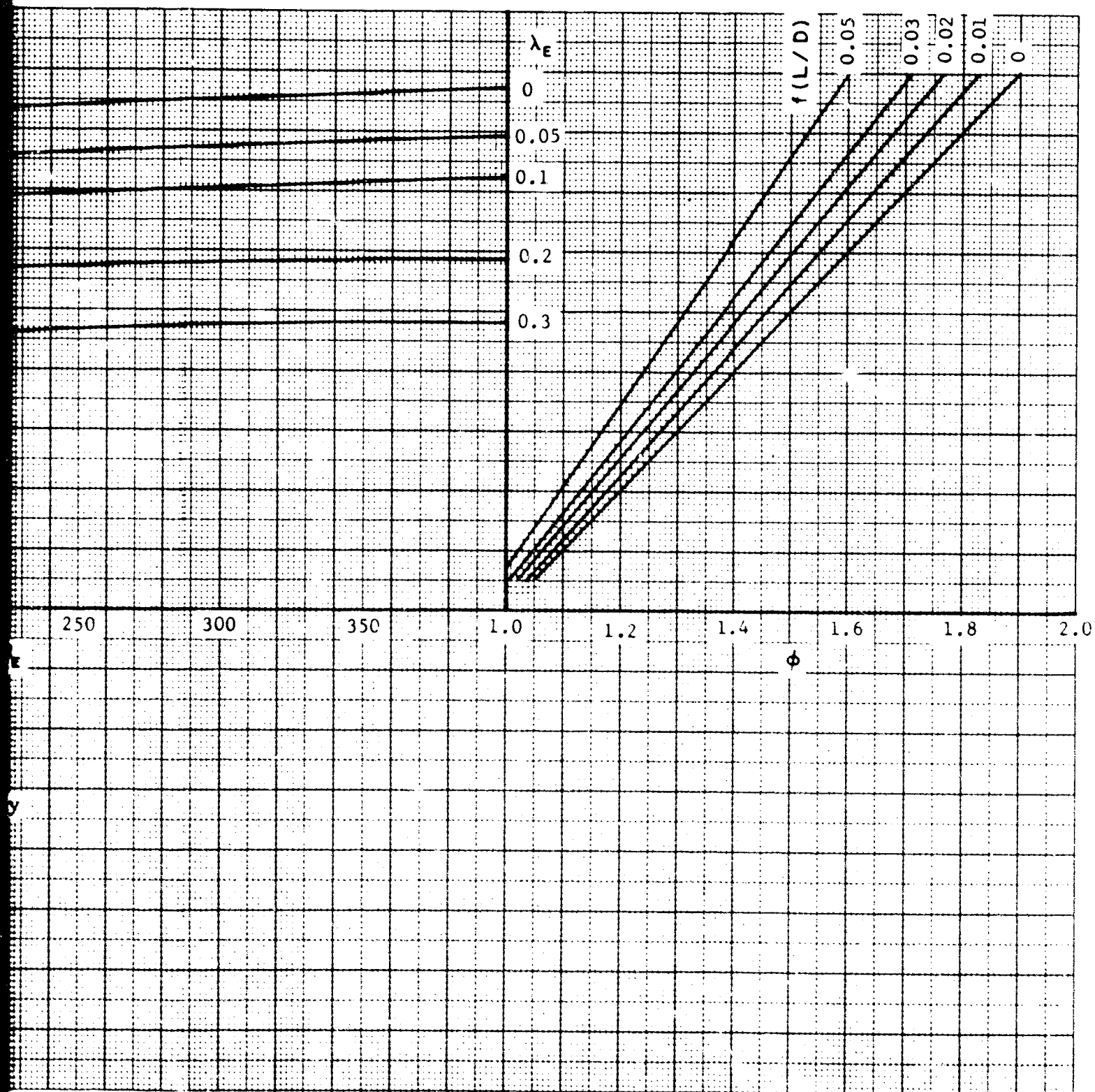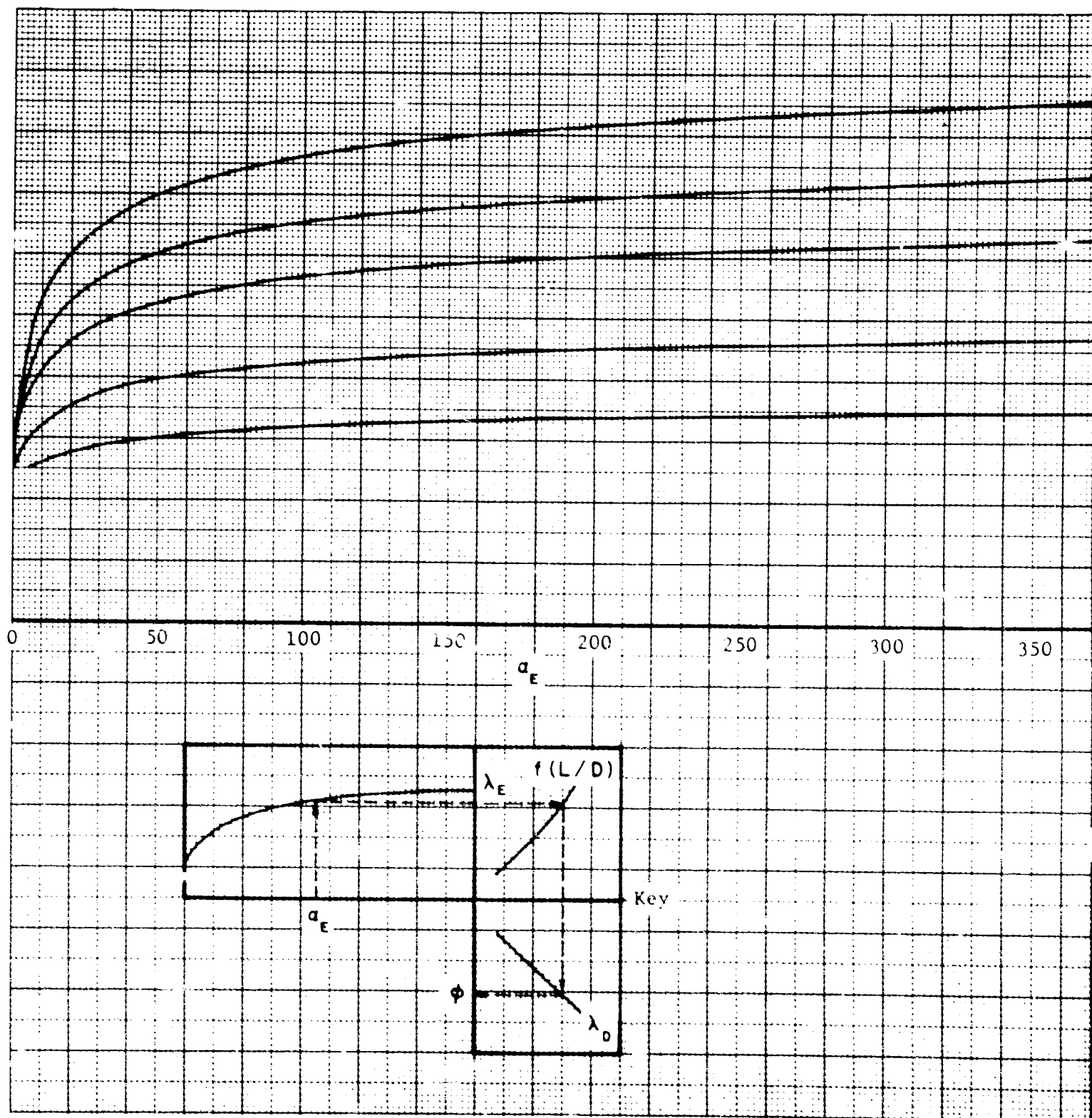
Figure 19. Nomograph for Thrust Augmentation Ratio - Incompressible
Flow Analysis Including Flow Losses $(a_D = 1.5, \mu = 0)$

99

H

λ_E

0

0.05

0.1

0.2

0.3

f (L/D)

0.05

0.03

0.02

0.01

0

250   300   350

1.0

1.5

ϕ

2.0

2.5

λ_0

0

0.1

0.2

0.3

0.4

Key
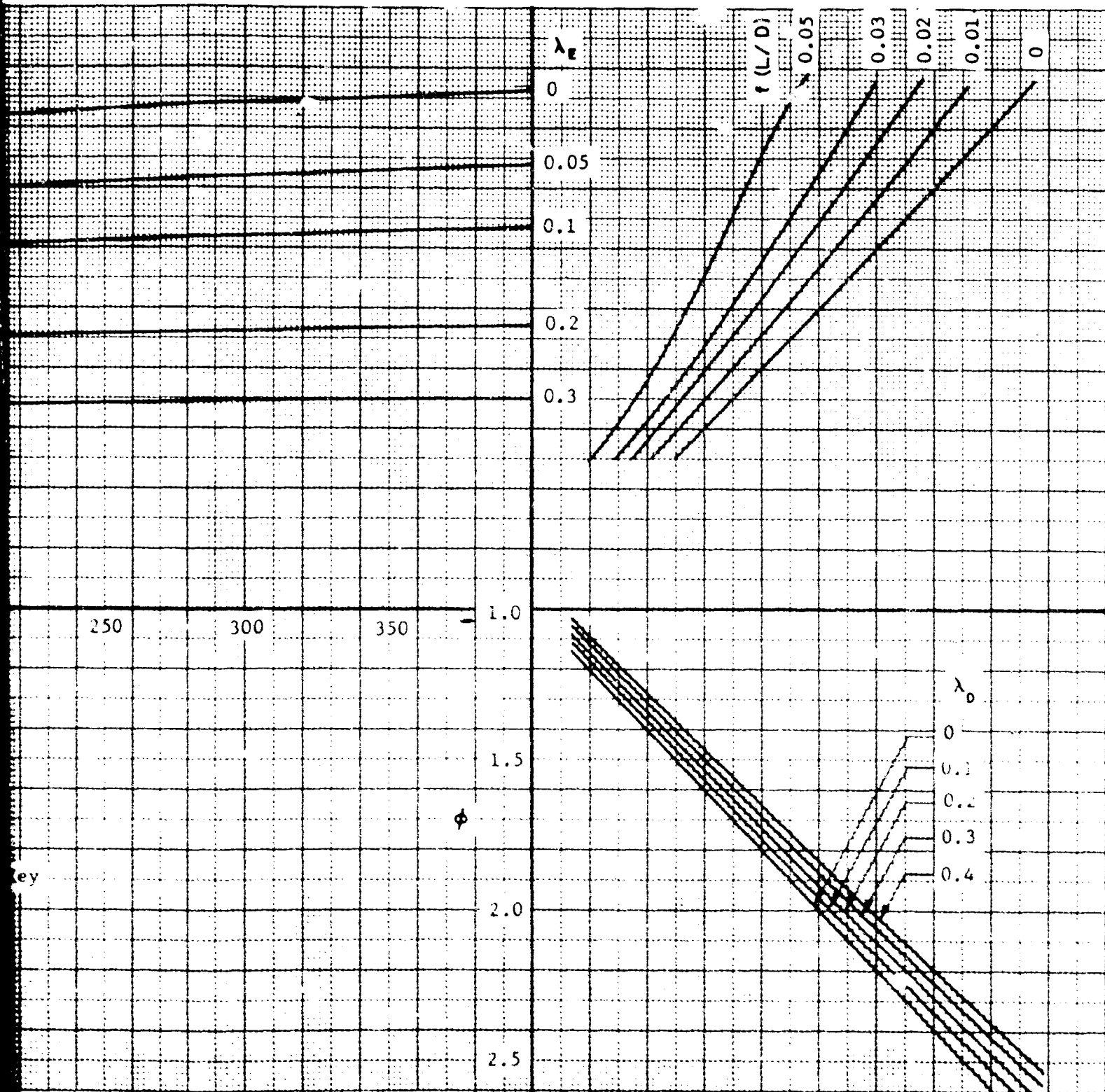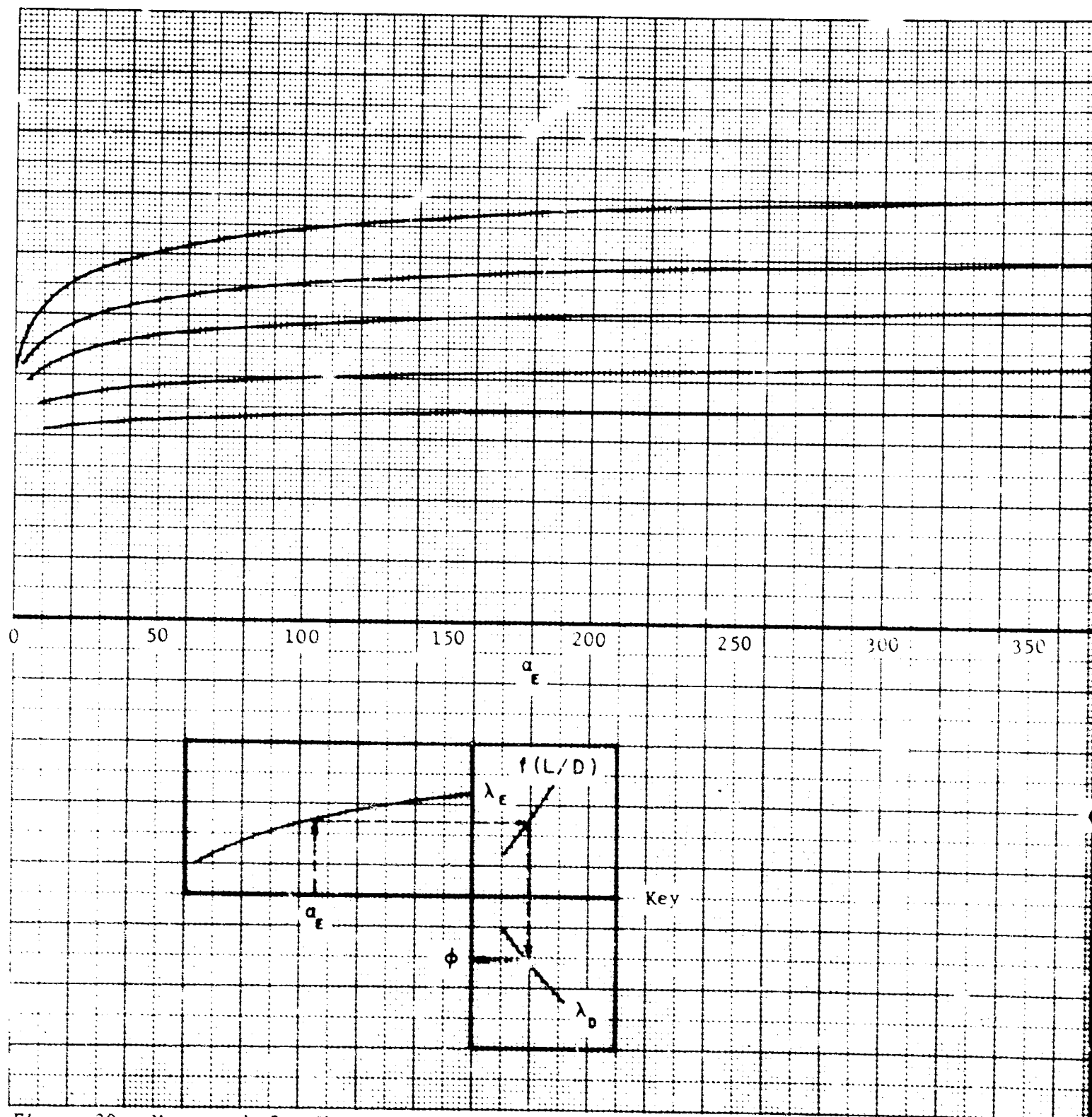
Incompressible

Figure 20. Nomograph for Thrust Augmentation Ratio - Incompressible
Flow Analysis Including Flow Losses ($a_0 = 2.0$; $\mu = 0$)

101

λ_E

f (L/D)

0.05 0.03 0.02 0.01 0

250   300   350   0

ϕ

1.0

2.0

Key

λ_D

0.4

0.3

0.2

0.1

0

3.0

4.0
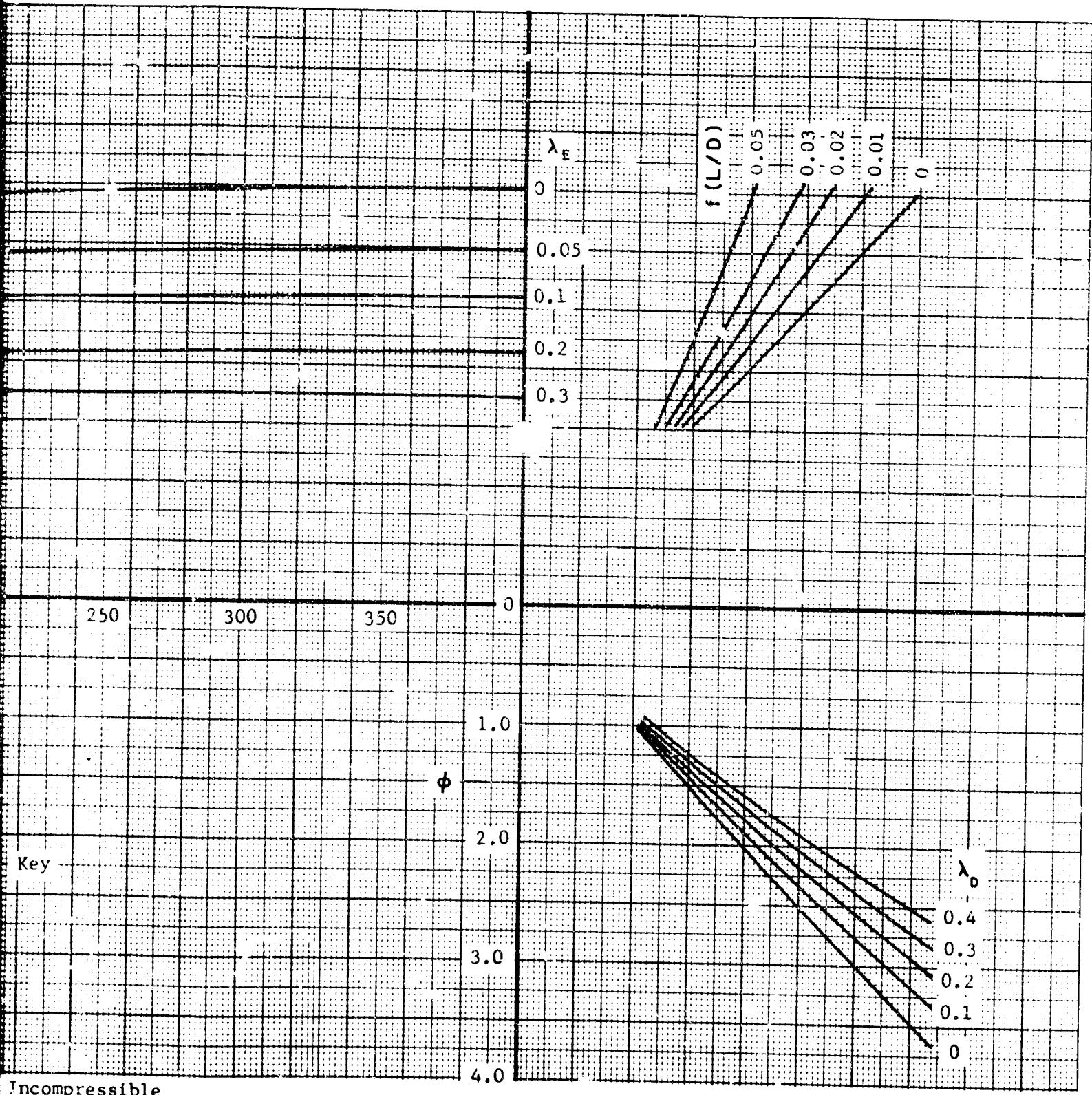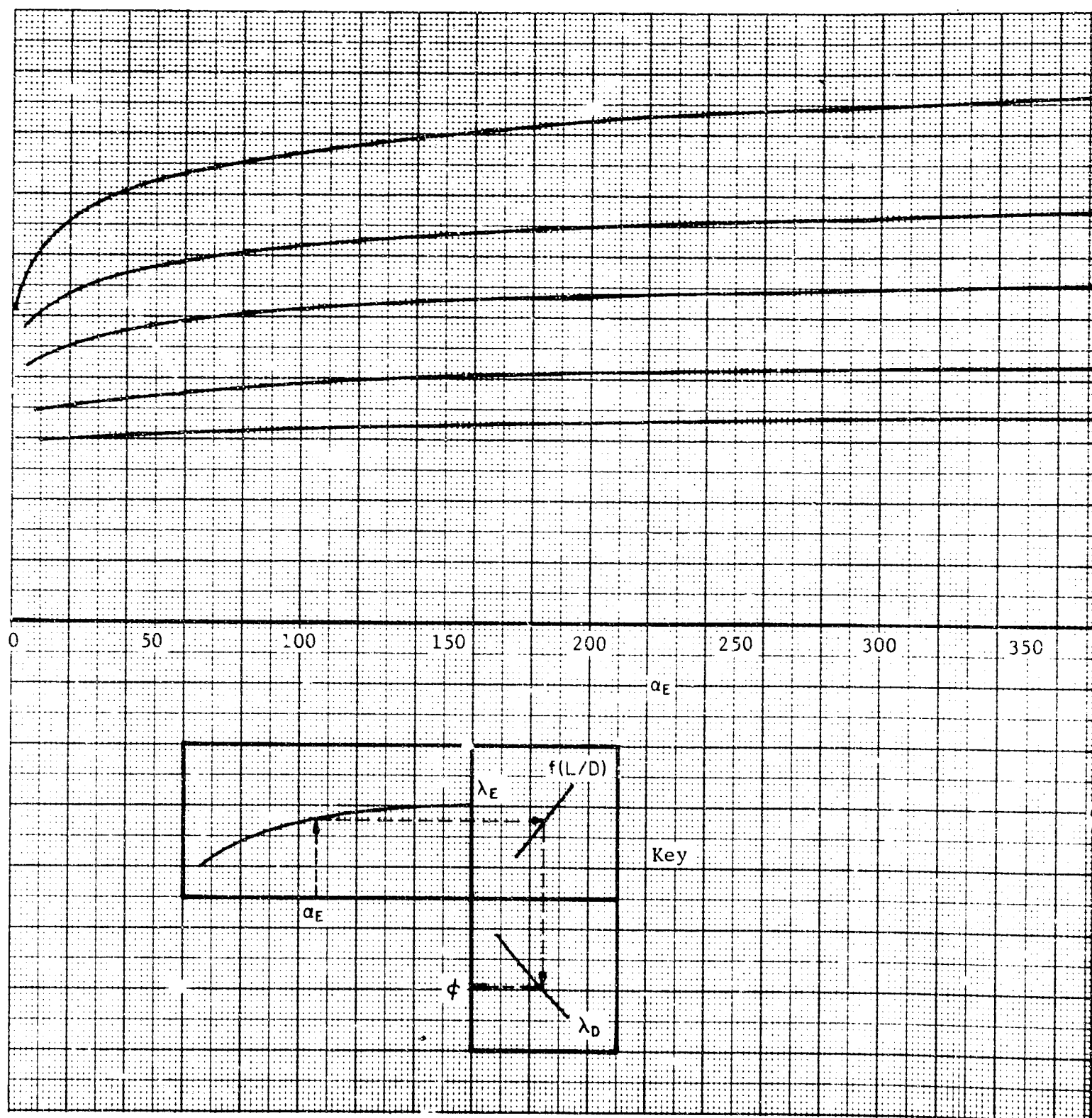
Incompressible

Figure 21. Nomograph for Thrust Augmentation Ratio - Incompressible
Flow Analysis Including Flow Losses ($a_D = 2.5; \mu = 0$)

103

λ_ε

0

0.05

0.1

0.2

0.3

f(L/D) 0.05 0.03 0.02 0.01 0

250   300   350

0

α_ε

Key

φ

1.0

2.0

3.0

4.0

λ_D

0.4

0.3

0.2

0.1

0
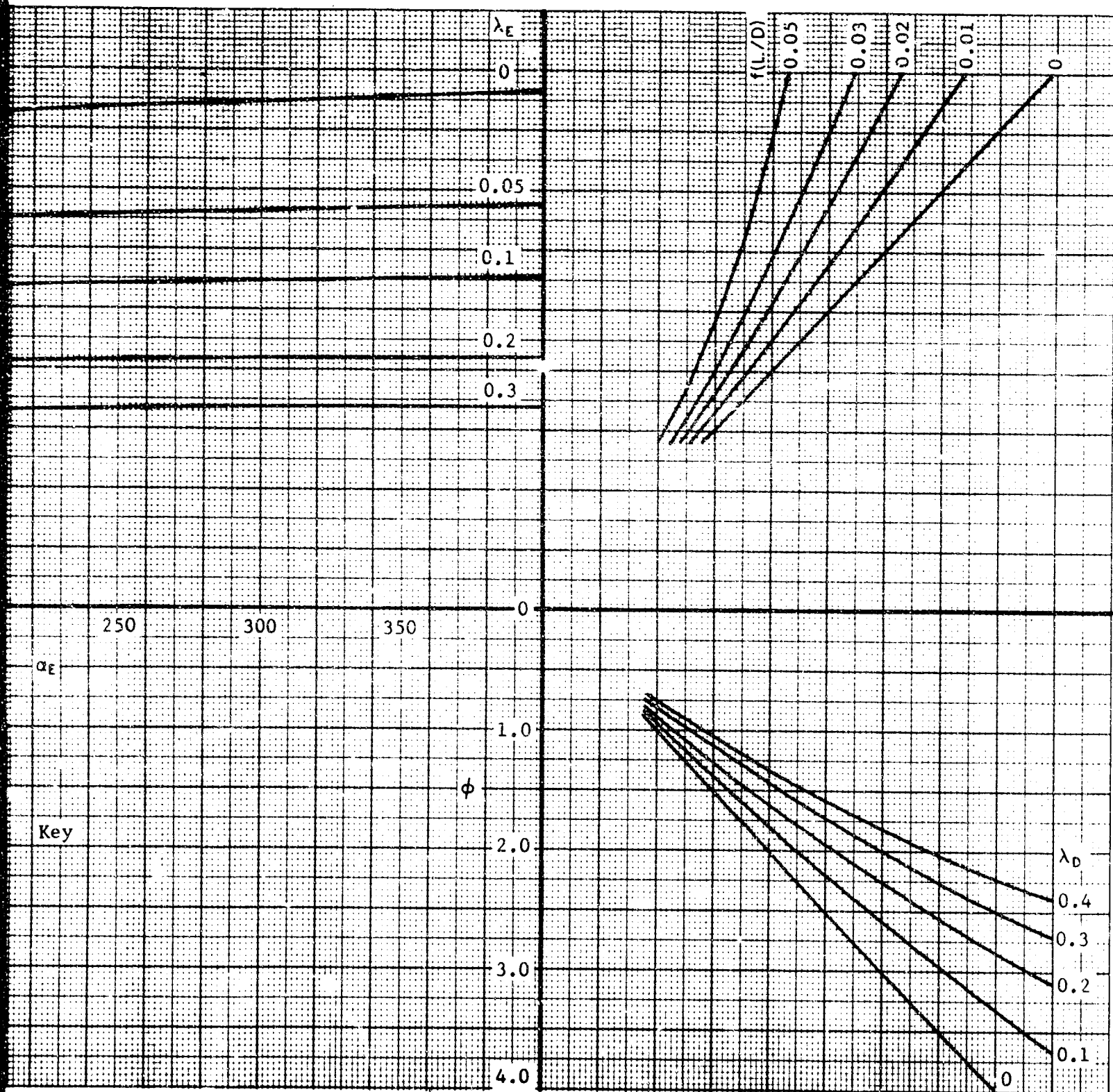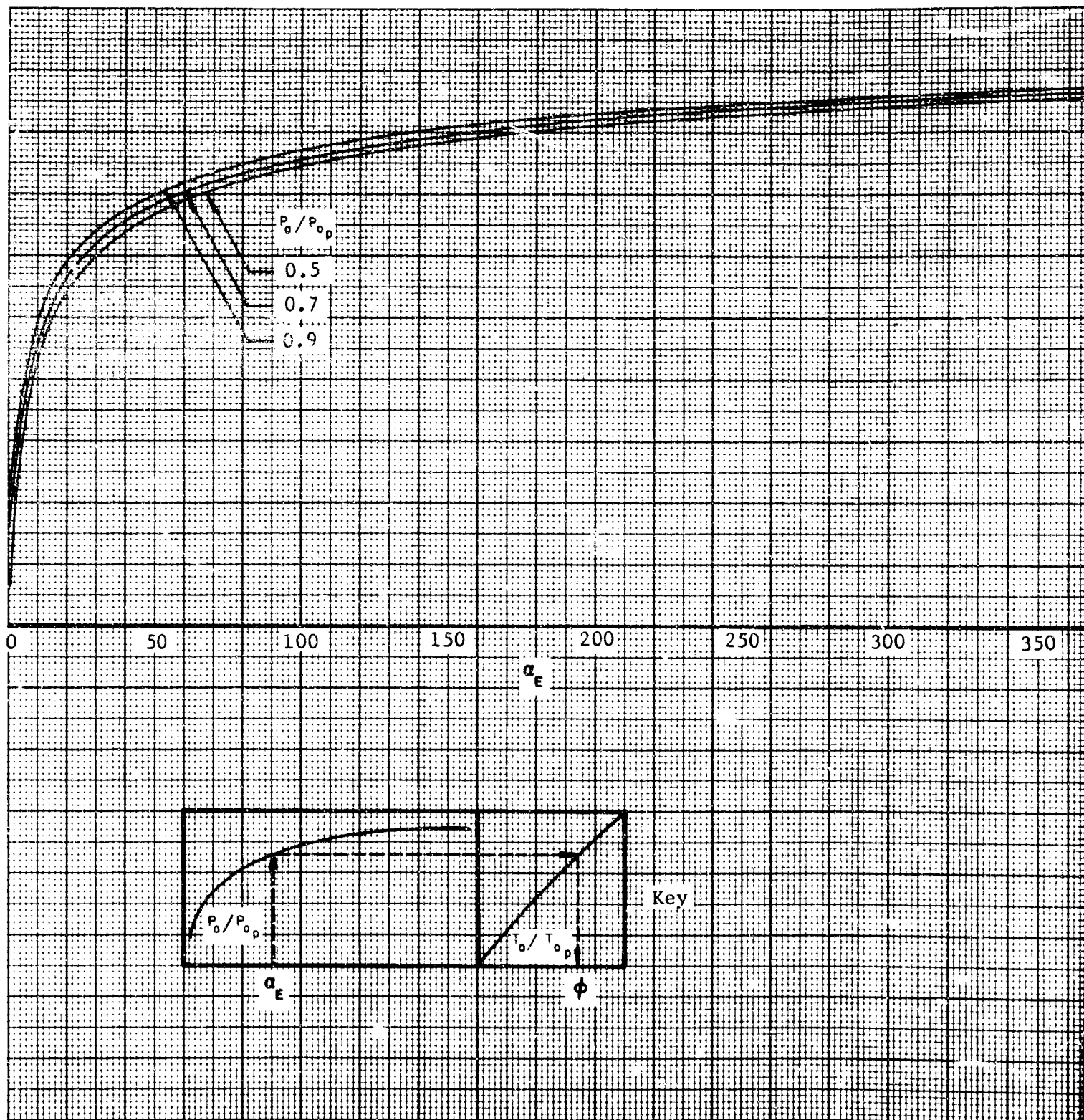
Incompressible

Figure 22. Nomograph for Thrust Augmentation Ratio - Compressible
Flow Analysis Neglecting Flow Losses ($\alpha_D = 1.0$; $\mu = 0$)

105

T_a/T_{n_p}

0.2
0.3
0.4
0.5
0.7
1.0

250   300   350   1.0   1.2   1.4   1.6   1.8   2.0

ϕ
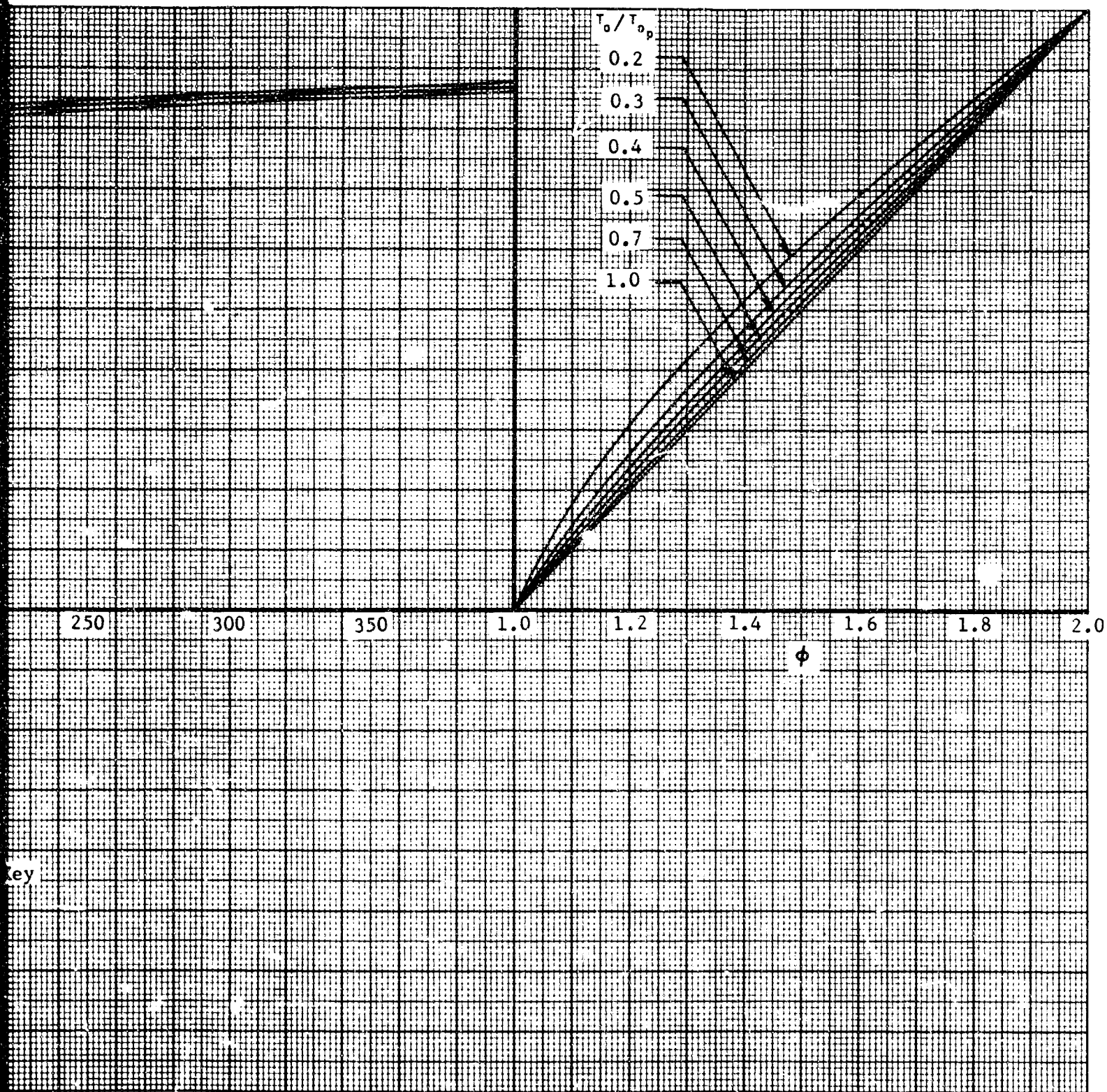
key

compressible

A   B

incompressible analysis (including flow losses) for the
diffuser area ratios $\alpha_D = 1.0, 1.5, 2.0,$ and 2.5,
respectively. The fifth nomograph, Figure 22, presents the
computer results for the compressible analysis for a wide
range of the nondimensionalized input parameters P_a/P_{0p}
and T_a/T_{0p}

1. Evaluation of Flow Losses

In utilizing the nomographs for the incompressible analysis,
the values of the various loss factors must be predetermined.
No precise information is available on these loss factors
which are dependent on the design and construction details
of the system. However, the following will serve as a
general guide:

    a. Friction Loss Factor f(L/D)

        The friction loss factor of a given jet ejector
        configuration is a function of the friction
        factor f along the ejector walls and the mixing
        chamber length-to-diameter ratio L/D required for
        complete flow mixing.

        The friction factor f = 0.003, which is commonly
        used for commercially smooth pipes is recommended
        to be used for fairly smooth mixing chamber walls
        of jet ejectors.

        No precise information is available for estimating
        the mixing chamber length-to-diameter ratios
        required for complete mixing. However, in order
        to provide the designer some basis for selection
        of the required L/D ratios, a semiempirical
        approach is herein utilized for estimating this
        parameter. This approach is based on the
        assumption that for a single nozzle jet ejector
        the flow losses due to partial mixing can be
        neglected provided that the mixing chamber length-
        to-diameter ratio is not less than 6.0. This
        implies that the flow mixing is considered to be
        complete for $L/D \geq 6.0$.

The results thus obtained are presented in
Figure 23. This figure can be utilized to
estimate the total mixing chamber length required
for complete flow mixing for single, multiple
(four evenly spaced nozzles), and annular jet
ejector configurations.

Thus, utilizing the friction factor of $f = 0.003$
and the L/D ratios from Figure 23, the required
friction loss factor $f(L/D)$ for any given jet
ejector configuration can be determined.

b. **Diffuser Loss Factor λ_D**

The diffuser loss factor λ_D is a function of a
total head loss within the diffuser, the dynamic
pressure at the diffuser entrance and its exit-to-
entrance area ratio. A mathematical definition of
this factor is presented in the list of symbols.
Some usable data for determining the loss factor
of various diffuser configurations is presented in
Reference 26.

c. **Secondary Entrance Loss Factor λ_E**

Very limited information is available for
determining the loss factor at the secondary
entrance. This factor is mainly a function of the
size and shape of the inlet, but it also depends on
the blockage effect of the components of the
ejector, such as manifolds, instrumentation, etc.,
located in the passage of the secondary flow
entrance. It is not possible to determine this
factor accurately, since it varies from case to
case. In Reference 27, representative values of
"internal inlet" loss factor, i.e., for static
conditions with no obstruction of the passage, are
presented as follows:

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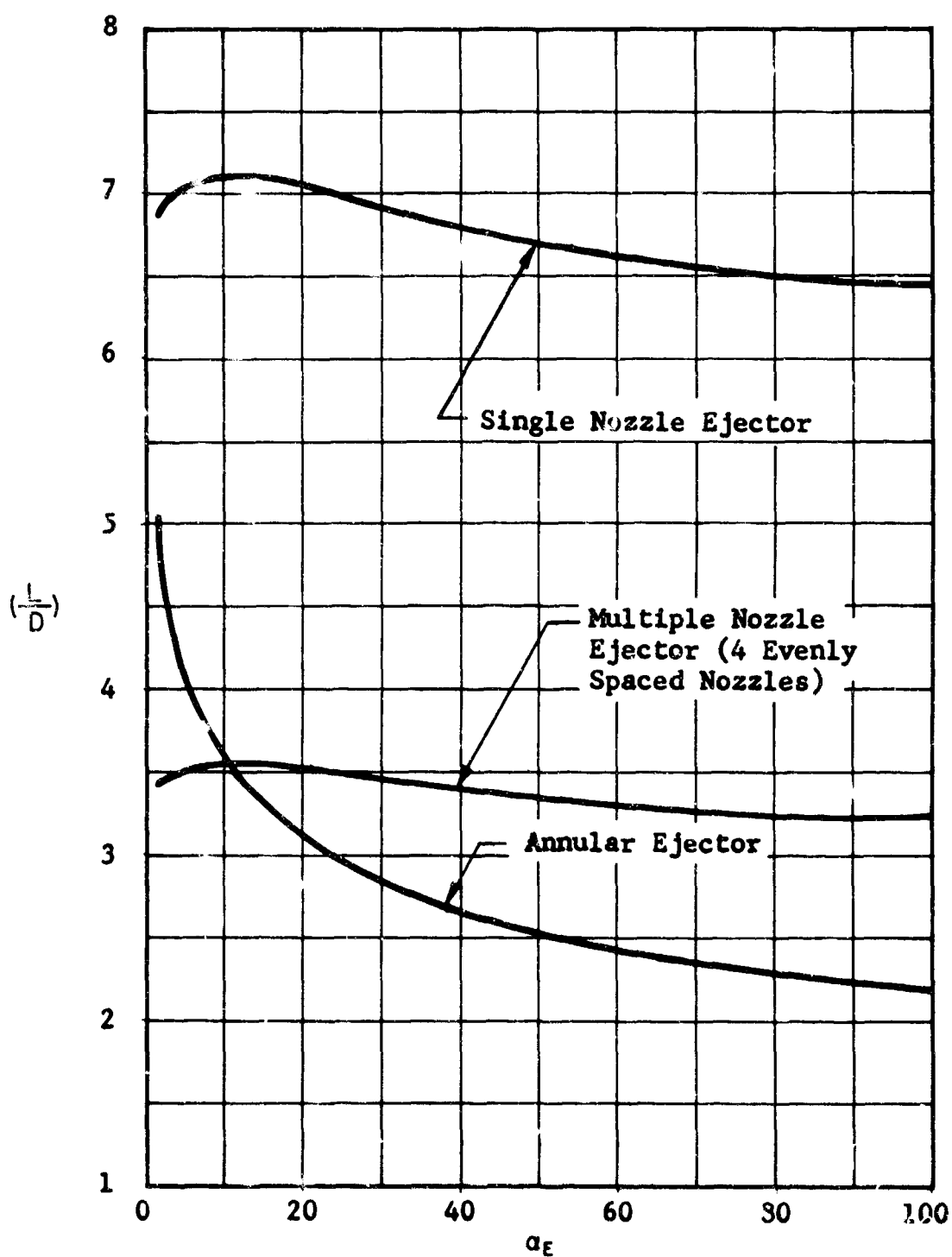
Figure 23. Variation of Minimum Mixing Chamber
Lengths Required for Complete Mixing for Various
Ejector Configurations (Idealized Analysis).

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Type of Entrance	λ_E
Flared	
Lemniscate contour	0.02
Circular contour	0.03
Straight contour	0.05
Rounded Edge	0.1
Sharp Edge	0.3

It can be noted from the above data that lemniscate lip contour is preferable in ejector designs. This contour tends to minimize adverse pressure gradient over the lip and thus results in lower entrance loss factor. Furthermore, in evaluating the entrance loss factor, a consideration must be given to the ratio of the entrance diameter to the mixing tube diameter. If this ratio is less than 1.5, an additional loss in thrust augmentation ratio may occur. This loss may be accounted for by appropriately increasing the entrance loss factor

2. Correction Factor for the Nonuniform Velocity Profile at the Secondary Entrance

Section IV contains an empirical analysis for determining the effect of a nonuniform velocity profile at the secondary entrance on jet ejector thrust augmentation. This analysis requires a knowledge of the flow nonuniformity parameter κ which can only be reliably predicted from appropriate experimental data.

The limited experimental data such as presented in Table II of Section VI indicates that the approximate value of this parameter is about $\kappa = 70$. Thus, using Figure 3, the empirical correction factor χ for thrust augmentation ratio due to nonuniform velocity profile at the secondary entrance can be determined as follows:

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$$\chi = \frac{\phi_{\kappa=70}}{\phi_I} \tag{150}$$

where $\phi_\kappa = 70$ is the thrust augmentation ratio with non-uniform secondary velocity profile for $\kappa = 70$, and ϕ_I is the ideal thrust augmentation ratio for the same α_E .

3. Compressibility Correction Factor C_C

The compressibility correction factor C_C can be obtained as the ratio of the compressible to the ideal value of thrust augmentation ratio ϕ for the same values of α_E and α_D . Thus:

$$C_C = \frac{\phi_C}{\phi_I} \tag{151}$$

The compressible value of thrust augmentation ratio ϕ_C can be obtained from the nomograph, Figure 22, for a given set of input conditions of P_a/P_{op} and T_a/T_{op}. The corresponding ideal value ϕ_I can be obtained from the nomograph, Figure 18, using $\lambda_E = f(L/D) = 0$.

4. Net Value of Thrust Augmentation Ratio

The net value of thrust augmentation ratio of a given ejector configuration can be expressed as follows:

$$\phi = \chi\, C_C\, \phi_L \tag{152}$$

where ϕ_L represents the incompressible value of thrust augmentation ratio including the effects of major flow losses. This value can be obtained from appropriate nomographs, Figures 18 to 21. Thus equation (152) can be used to predict the total thrust augmentation ratio of a given

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ejector configuration including the effects of nonuniform
entrance velocity, flow compressibility, and major flow
losses discussed above.

5. Use of the Nomographs

The procedure for determining ejector thrust augmentation
performance requires the use of the nomographs presented in
Figures 18 to 22. In order to utilize these charts, it is
first necessary to determine ejector geometry, major flow
losses, and operating conditions of a given jet ejector
configuration. The use of the nomograph is explained
graphically in the key of each chart.

The procedure for the use of nomographs for a general case
of an ejector with a diffuser is as follows:

(a) Select an appropriate nomograph for a given
    diffuser exit-to-entrance area ratio λ_D.

(b) On the upper left-hand plot of the nomograph,
    draw a vertical line at a given α_E to intersect
    with the curve corresponding to the computed
    value of entrance loss factor λ_E. Interpolate
    between λ_E curves if required.

(c) From the point of intersection of step (b),
    project a horizontal line to intersect with the
    curve corresponding to the computed value of the
    friction loss factor $f(L/D)$. Interpolate between
    $f(L/D)$ curves if required.

(d) From the point of intersection of step (c), draw a
    vertical line to intersect the curve corresponding
    to the computed value of the diffuser loss factor
    λ_D . Interpolate between λ_D curves if required.

(e) From the point of intersection of step (d), draw
    a horizontal line to intersect with the scale of
    the thrust augmentation ratio. Read off this
    value of thrust augmentation ratio ϕ_L, which in
    this case would correspond to the incompressible
    value including the flow losses and the effect of
    a diffuser.

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Similar procedure is applied in the use of the nomograph for an ejector without diffuser (Figure 18), except that the vertical line of step (d) is drawn to intersect the horizontal scale of thrust augmentation ratio. The point of intersection of the vertical line with the scale yields the required value of ϕ_L with no diffuser.

The procedure for the use of the nomograph (Figure 22) to determine the compressible value of thrust augmentation ratio is similar to that described above. However, in this case the nomograph is entered using the precomputed values of ambient-to-stagnation pressure and temperature ratios, P_a/P_{0p} and T_a/T_{0p} respectively.

In the cases where the ejector performance is required for some intermediate values of diffuser area ratios α_D, the usual interpolation procedures between the nomographs can be utilized.

6. Limitations of the Nomographs

Although the nomographs (Figures 18 to 22) represent a rapid and a practical analytical tool in evaluating performance of a given jet ejector configuration, the usefulness of the charts is limited by the assumptions inherent in the analysis.

The major problem exists in the user's ability to accurately predetermine the required flow losses of a given ejector configuration.

The assumptions used to determine the friction factor along the mixing chamber walls ($f = 0.003$), the total mixing chamber length for complete mixing, and the flow nonuniformity parameter ($\kappa = 70$) for the velocity profile at the secondary entrance require further experimental verification

The nomographs have been carefully prepared and their accuracy is expected to be within ± 3 percent of the computer results.

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C. PROCEDURE FOR DETERMINING PERFORMANCE OF A GIVEN JET
    EJECTOR CONFIGURATION

The following procedure can be utilized to determine the
performance of a given jet ejector configuration:

(i) Determine the following geometric parameters
     and operation conditions:

     (a) Type of ejector configuration

     (b) Number of primary nozzles, N

     (c) Secondary-to-primary area ratio, α_E

     (d) Diffuser exit-to-entrance area ratio, α_D

     (e) Diffuser length and expansion angle

     (f) Mixing chamber shape

     (g) Ejector intake geometry

     (h) Ejector operating conditions, P_a/P_{op}
          and T_a/T_{op}

(ii) Knowing α_E and the type of ejector configuration,
      enter Figure 23 and obtain the total mixing
      chamber length (L/D) required for complete mixing.
      For the case of a multiple nozzle ejector configu-
      ration with N ≠ 4.0, determine the total mixing
      chamber length using the following equation:

$$\left(\frac{L}{D}\right)_M = \frac{1}{\sqrt{N}}\left(\frac{L}{D}\right)_S \tag{153}$$

where $(L/D)_S$ can be obtained from Figure 23.

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(iii) Assuming friction factor $f = 0.003$, compute ejector friction loss factor $f(L/D)$ using (L/D) value from step (ii).

(iv) Using data of Reference 26 (or other pertinent data) and the diffuser geometry from step (i), determine diffuser loss factor λ_D .

(v) Using data of Reference 27 (or other pertinent data) and ejector intake geometry from step (i), determine the ejector entrance loss factor λ_E .

(vi) With the flow losses determined in steps (iii) to (v) and known values of α_E and α_D from step (i), enter the appropriate nomograph and obtain the incompressible value of thrust augmentation ratio including flow losses, ϕ_L .

(vii) Using α_E from step (i) and assuming $\kappa = 70$, enter Figure 3 and obtain $\phi_{\kappa=70}$ and ϕ_I . Then compute the empirical correction factor χ from equation (150). This factor accounts for the reduction of thrust augmentation ratio due to nonuniform velocity profile at the secondary entrance.

(viii) Using the operation conditio. of P_0/F_{0p} and T_0/T_{0p} and α_E from step (i), enter nomograph Figure 22 and determine the compressible value of thrust augmentation ratio ϕ_C . Also, enter Figure 18 using $\lambda_E = f(L/D) = 0$ and obtain ideal value of thrust augmentation ratio ϕ_I . Then compute the compressibility correction factor C_C using equation (151).

(ix) Using ϕ_L from step (vi), χ from step (vii), and C_C from step (viii), compute the required thrust augmentation ratio from equation (152).

(x) For a known mixing chamber shape, compute mass entrainment ratio w using equation (34) for constant area mixing or equation (51) for constant

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pressure mixing. The mass entrainment ratio for compressible analysis or incompressible analysis including major flow losses can be most conveniently obtained using the computer program described in Appendix I.

D. SAMPLE CALCULATION

To more clearly indicate the analytical procedures for determining ejector performance, a sample calculation is performed as follows:

(i) Assume a single, central nozzle configuration of constant area mixing chamber having $\alpha_E = 100$ and $\alpha_D = 2.0$. Also assume the following operation conditions $T_0 = 70°F$, $T_{0p} = 600°F$, $P_0 = 14.7 \text{ lb/in}^2$, and $P_{0p} = 21 \text{ lb/in}^2$.

Compute

$$\frac{T_0}{T_{0p}} = \frac{70+460}{600+460} = \frac{530}{1060} = 0.5$$

$$\frac{P_0}{P_{0p}} = \frac{14.7}{21.0} = 0.7$$

(ii) Using $\alpha_E = 100$, enter Figure 23 and obtain

$$\left(\frac{1}{D}\right)_s = 6.43$$

(iii) Assuming friction factor $f = 0.003$, calculate ejector friction loss factor using $(L/D) = 6.43$ from step (ii). Thus,

$$f(L/D) = 0.003 \times 6.43 = 0.0193$$

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(iv) Using data of Reference 26, determine the
diffuser loss factor

$$\lambda_D = 0.2$$

(v) Using data of Reference 27, determine entrance
loss factor

$$\lambda_E = 0.1$$

(vi) With the flow losses computed in steps (iii) to
(v) and using $\alpha_E = 100$, $\alpha_D = 2.0$, enter
nomograph Figure 20 and determine the incompressible
value of thrust augmentation ratio including flow
losses

$$\phi_L = 1.98$$

(vii) Assuming $\kappa = 70$ and using $\alpha_E = 100$, enter
Figure 3 and obtain

$$\phi_{\kappa=70} = 1.745$$

$$\phi_I = 1.776$$

Compute the empirical correction factor χ for
thrust augmentation ratio due to nonuniform
velocity profile at the secondary entrance; thus,

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$$\chi = \frac{\phi_{K=70}}{\phi_I} = \frac{1.745}{1.776} = 0.983$$

(viii)   Using the values $P_a/P_{0p} = 0.7$ and $T_a/T_{0p} = 0.5$
         computed in step (i), enter nomograph Figure 22
         and obtain the compressible value of thrust
         augmentation ratio corresponding to $\alpha_E = 100$.
         Thus,

$$\phi_C = 1.737$$

         Also enter nomograph Figure 18 using
         $\lambda_E = f(L/D) = 0$ and $\alpha_E = 100$ and determine
         ideal value of thrust augmentation ratio. Thus,

$$\phi_I = 1.776$$

         Compute compressibility correction factor

$$C_C = \frac{\phi_C}{\phi_I} = \frac{1.737}{1.776} = 0.978$$

(ix)   Finally, using $\phi_L = 1.98$ (from step (vii),
       $\chi = 0.983$ (from step (vii)), and $C_C = 0.978$
       (from step viii), compute the required thrust
       augmentation ratio as follows:

$$\phi = \phi_L \chi C_C = 1.98 \times 0.983 \times 0.978 = 1.90$$

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(x) Using $\alpha_E = 100$ and $\alpha_D = 2.0$, compute mass entrainment ratio w from equation (34); thus,

$$w = \frac{(\alpha_E + 1)\alpha_D\left[-(\alpha_E - 1)\alpha_D + \alpha_E\sqrt{\alpha_D^2 + 2\alpha_E - 1}\right] - (\alpha_E^2 + \alpha_D^2)}{\alpha_E^2 + \alpha_D^2}$$

$$w = \frac{(100 + 1)2\left[(100 - 1)2 + 100\sqrt{2^2 + 2\times100 - 1}\right] - (100^2 + 2^2)}{100^2 + 2^2}$$

$$= \frac{202\left[-198 + 100\sqrt{103}\right] - 10004}{10004} = 15.49$$

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VIII. CONCLUSIONS AND RECOMMENDATIONS

1. A review of the technical literature shows that the existing analytical and experimental information on the thrust augmentation characteristics of jet ejectors cannot be used as an effective design tool.

2. The analysis performed in this report indicates that a constant area mixing ejector yields a higher thrust augmentation ratio than an equivalent constant pressure mixing configuration.

3. For any practical value of secondary-to-primary area ratio, the thrust augmentation ratio reaches an optimum value with the diffuser area ratio ranging between 1.5 and 2.0.

4. To obtain a maximum thrust augmentation, the mixing chamber length should be compromised so as to achieve the best mixing with a minimum wall friction.

5. Annular and multiple nozzle ejectors require substantially shorter mixing chamber lengths for complete mixing as compared to an equivalent single, central nozzle configuration.

6. The flow losses have a predominant effect on jet ejector performance, whereas flow compressibility is only of secondary importance.

7. An increase of forward speed (parallel or perpendicular to the ejector) causes a decrease of the thrust augmentation ratio.

8. The available test data are insufficient to determine reliably the validity of the assumptions utilized in the analyses. It is therefore recommended that a systematic test program be conducted to determine the applicability of these assumptions as well as to provide more precise information to evaluate the empirical correction factors presented in this report.

IX. REFERENCES

1. Roy, M., *Theoretical Investigation on the Efficiency and the Conditions for the Realization of Jet Engines*, TM 1259, NACA, June 1950.

2. Morrisson, R., *Jet Ejectors and Augmentation*, ACR, September 1942.

3. Sargent, E. R., *Theoretical Performance of a Static Thrust Augmenter*, Report No. R-150, Curtiss-Wright Corporation, Airplane Division, St. Louis, Missouri, July 1944.

4. Sargent, E. R., *Theoretical Performance of a Dynamic Thrust Augmenter*, Report No. R-158, Curtiss-Wright Corporation, Airplane Division, St. Louis, Missouri, July 1944.

5. McClintock, F. A., and Hood, H. H., "Aircraft Ejecter Performance", *Journal of the Aeronautical Sciences*, Volume 13, No. 11, November 1946, pp. 559-568.

6. Ellerbrock, H. H., Jr., *General Treatment of Compressible Flow in Ejectors and Example of Its Application to Problem of Effect of Ejector Addition on Thrust of Jet Propulsion U. s*, .wi LoL23, NACA, June 1947.

7. von Kármán, T., "Theoretical Remarks on Thrust Augmentation", *Reissner Anniversary Volume*, W. Edwards, Ann Arbor, Michigan, 1949, pp. 461-468.

8. Szczeniowski, B., *Theory of the Jet Syphon*, TN 3385, NACA, May 1955.

9. Sanders, J. C., and Brightwell, V. L., *Analysis of Ejector Thrust by Integration of Calculated Surface Pressures*, TN 1958, NACA, October 1949.

10. Bertin, J., and le Nabour, M., "Contribution au Developpement des Trompes et Ejecteurs", *Technique et Sciences Aeronautiques*, Tome 3, May-June 1959, pp. 127-138.

11. Chisholm, R. G. A., Design and Calibration of an Air Ejector to Operate Against Various Back Pressures, UTIA Tech. Note No. 39, University of Toronto, Institute of Aerophysics, Toronto, Canada, September 1960.

12. Reid, J., The Effect of a Cylindrical Shroud on the Performance of a Stationary Convergent Nozzle, R. & M. No. 3320, Aeronautical Research Council, London, Britain, January 1962.

13. Martin Company, Recirculation Principle for Ground Effect Machine. Two-Dimensional Tests, TCREC Technical Report 62-66. United States Army Transportation Research Command, Fort Eustis, Virginia, June 1962.

14. Storkebaum, C., Die Unwendung des Ejektor bei V/STOL-Flugzeugen und dessen Auslegung, DFL-Bericht Nr. 234 and DLR FB 62-25, Deutsche Forschungsanstalt fuer Luft- und Raumfahrt E. V., Braunschweig, Germany, February and August 1964.

15. Wan, C. A., A Study of Jet Ejector Phenomena, Research Report No. 57, Mississippi State University, Aerophysics Department, State College, Mississippi, November 1964.

16. Payne, P. R., Steady-State Thrust Augmentors and Jet Pumps, USAAVLABS Technical Report 66-18, United States Army Aviation Materiel Laboratories, Fort Eustis, Virginia, March 1966.

17. Sandover J. (Editor), The Jet-Pump as an Alternative Means of Providing Lift in Air-Cushion Vehicles, Report No. 20, Norman K. Walker Associates, Incorporated, Bethesda, Maryland, August 1965.

18. Payne, P. R., and Anthony, A., Tests of Three Axisymmetric Model Eductors, Report No. 57, Peter R. Payne Associates, Rockville, Maryland, November 1964.

19. Squire, H. B., and Trouncer, J., <u>Round Jets in a</u>
    <u>General Stream</u>, Reports and Memoranda No. 1974,
    Aeronautical Research Committee, London, Britain,
    January 1944.

20. Mikhail, S., "Mixing of Coaxial Streams Inside a Closed
    Conduit", <u>Journal of Mechanical Engineering Science</u>,
    Volume 2, No. 1, March 1960, pp. 59-68.

21. Johnson, J. K., Jr., Shumpert, P. K., and Sutton, J. F.,
    <u>Steady Flow Ejector Research Program</u>, ER-5332,
    Lockheed Georgia Company, Marietta, Georgia,
    September 1961.

22. Gates, M. F., and Fairbanks, J. W., <u>Summary Report -</u>
    <u>Phase III Program. Annular Nozzle Ejector</u>, Report
    No. ARD-300, Hiller Aircraft Corporation, Palo Alto,
    California, December 1961.

23. Chaplin, H. R., <u>Theory of the Annular Nozzle in Proximity</u>
    <u>to the Ground</u>, Aero Report 923, David W. Taylor Model
    Basin, Washington, D. C., July 1957.

24. von Glehn, U. H., <u>Exploratory Study of Ground Proximity</u>
    <u>Effects on Thrust of Annular and Circular Nozzles</u>,
    TN 3982, NACA, 1957.

25. Forstall, W., Jr., and Shapiro, A. H., <u>Momentum and</u>
    <u>Mass Transfer in Coaxial Gas Jets</u>, Project Meteor
    Report No. 39, Massachusetts Institute of Technology,
    Cambridge, Massachusetts, July 1949.

26. Henry, J. R , Wood, C. C., and Wilbur, S. W. <u>Summary of</u>
    <u>Subsonic-Diffuser Data</u>, RM L56F05, NACA, October 1956.

27. Henry, J. R., <u>Design of Power-Plant Installations,</u>
    <u>Pressure-Loss Characteristics of Duct Components</u>,
    ARR No. L4F26, NACA, June 1944.

28. Payne, P. R., "The Development of Ducted Rocket Power
     Units for Models", <u>Proceedings of the First Model
     Aeronautic Conference</u>, The Royal Aeronautical Society,
     London, Britain, September 1954.

29. Campbell, P. J., <u>Ground Tests of Exhaust Gas Thrust
     Augmenters</u>, United Aircraft Corporation, East
     Hartford, Connecticut, November 1940.

30. Drummond, A. M., and Gould, D. G., <u>Experimental Thrust
     Augmentation of a Variable Geometry, Two-Dimensional,
     Central Nozzle Ejector</u>, Report LR-328, National
     Research Laboratories, Ottawa, Canada, January 1962.

31. Slatter, B. H., and Bailey, W., <u>Notes on Simple Thrust
     Augmentation for Jet Propulsion Units</u>, R.A.E.
     Technical Note Eng. 121, Royal Aircraft Establishment,
     Farnborough, Britain, March 1943.

32. Storkebaum, C., <u>Die Anwendung des Ejektors bei V/STOL-
     Flugzeugen und dessen Auslegung. 3. Teilbericht</u>,
     Forschungsbericht 65-25, Deutsche Forschungsanstalt
     fuer Luft- und Raumfahrt, Braunschweig, Germany,
     April 1965.

33. Rabeneck, G. L., Shumpert, P. K., and Sutton, J. F.,
     <u>Steady Flow Ejector Research Program</u>, ER-4708,
     Lockheed Aircraft Corporation, Georgia Division,
     Marietta, Georgia, December 1960.

34. Guienne, P., "Ejectors, or the Ejector Wing, Applied to
     V/STOL Aircraft", <u>Journal of the American Helicopter
     Society</u>, Volume 6, No. 3, July 1961, pp. 2-9.

APPENDIX I

COMPUTER PROGRAMS FOR SOLUTION OF FLOW EQUATIONS
FOR THE PRACTICAL ANALYSIS

Due to the complexity of the flow equations which require
tedious and lengthy computation, it was decided that a more
efficient and accurate method of obtaining the required
results would be by the use of a digital computer. The
practical analysis presented in Section IV was therefore
programmed on an IBM 360 computer utilizing BPS FORTRAN IV
language. Two separate prog...ms were performed. The first
program deals with the incompressible flow analysis whereby
major flow losses and the effect of a diffuser and forward
speed are included. The second program deals exclusively
with flow compressibility.

1. Incompressible Flow Analysis

As mentioned previously, the effect of the major flow losses,
diffuser, and forward speed are investigated on the basis of
the incompressible flow analysis. This is accomplished by
solving equation (57) for the velocity ratio V_3/V_{1_p}. The
velocity ratio V_{1_s}/V_{1_p} is then computed from equation (58).
The thrust augmentation ratio ϕ and mass entrainment ratio w
are obtained from equations (60) and (62), respectively. A
simplified flow diagram of this program is presented in
Figure 24, and a typical IBM computer output is shown in
Table XIV.

2. Compressible Flow Analysis

The compressible flow analysis as presented in Section IV
involves a simultaneous solution of the two nonlinear
equations (85) and (86) for the two unknowns V_2/V_{a_p} and
T_{1_p}/T_{a_p} in terms of given input parameters P_a/P_{0_p}, T_a/T_{0_p},
and α_E. However, in generating the required computer data,
equations (85) and (86) are solved in their equivalent
dimensional form as follows:

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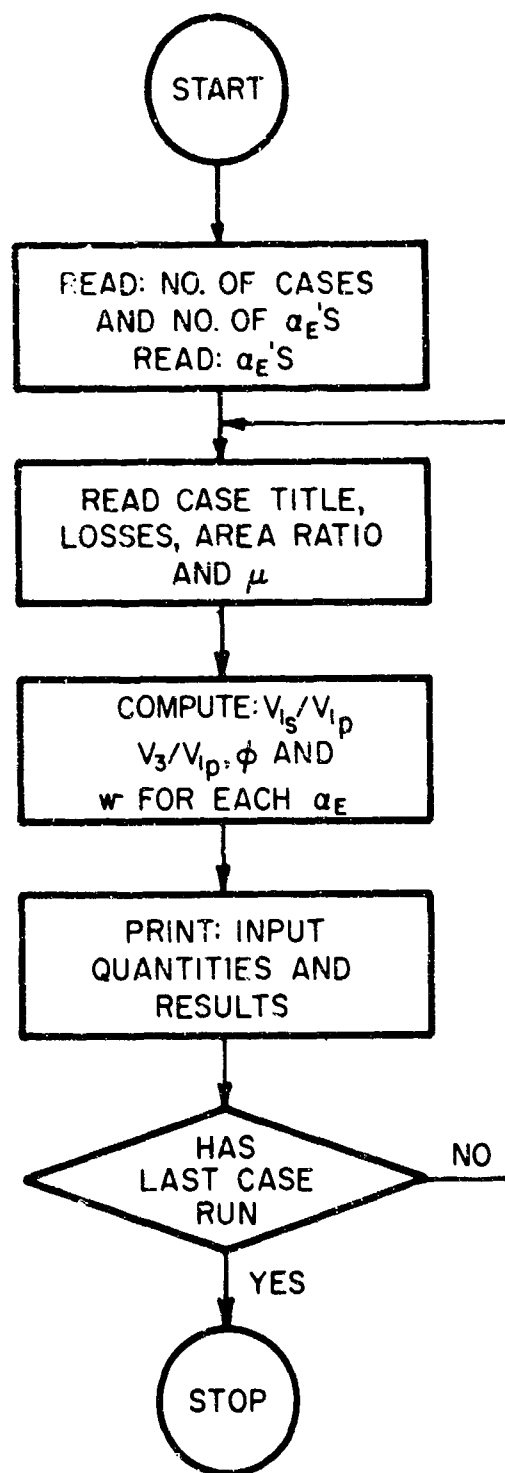
Figure 24.   Computer Flow Diagram
for Incompressible Analysis.

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TABLE XIV

TYPICAL COMPUTER RESULTS FOR INCOMPRESSIBLE ANALYSIS

CASE 1

DIFFUSER AREA RATIO= 0.20000E 01   LAMBDA-E= 0.10000E 00
FRICTION FACTOR= 0.10000E-01   LAMBDA-D= 0.20000E 00
VINF/VAP= 0.50000E-01   NO. OF ALPHAS= 10

I	ALPHA	PHI	ENT RATIO	VIS/VIP	V3/V1P
1	0.10000E 00	0.14974E 01	0.76802E-01	0.76892E 00	0.48950E 00
2	0.10000E 01	0.14544E 01	0.69139E 00	8.69139E 00	0.42285E 00
3	0.50000E 01	0.14451E 01	0.26513E 01	0.53025E 00	0.30427E 00
4	0.10000E 02	0.14440E 01	0.44154E 01	0.44154E 00	0.24616E 00
5	0.50000E 02	0.13434E 01	0.12799E 02	0.25599E 00	0.13529E 00
6	0.10000E 03	0.12168E 01	0.19770E 02	0.19770E 00	0.10282E 00
7	0.25000E 03	0.93104E 00	0.35666E 02	0.14266E 00	0.73036E-01
8	0.50000E 03	0.58071E 00	0.57732E 02	0.11546E 00	0.58615E-01
9	0.10000E 04	0.14832E-01	0.97985E 02	0.97985E-01	0.49443E-01
10	0.50000E 04	-0.38282E 01	C.40217E 03	0.80435E-01	0.40309E-01

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$$\frac{\rho_{lp}}{g}\left\{\sqrt{2\,g\,c_p T_{op}J\left[1-\left(\frac{\gamma-1}{\gamma}\cdot\frac{\rho_{lp}c_p T_{op}J}{P_{op}}\right)^{\gamma-1}\right]}+\right.$$

$$\left.\alpha_E\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{op}}{T_a}\right)\sqrt{2\,g\,c_p T_a J\left[1-\left(\frac{P_{op}}{P_a}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{\gamma-1}{\gamma}\cdot\frac{\rho_{lp}c_p T_{op}J}{P_{op}}\right)^{\gamma-1}\right]}\right\}V_2+$$

$$(\alpha_E+1)P_a-\rho_{lp}c_p T_{op}J\left[(\alpha_E+1)\frac{\gamma-1}{\gamma}\left(\frac{\rho_{lp}c_p T_{op}J}{P_{op}}\right)^{\gamma-1}-2-2\alpha_E\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\right]=0$$

$$\dots(154)$$

$$\frac{\rho_{lp}}{2g}\left\{\sqrt{2\,g\,c_p T_{op}J\left[1-\left(\frac{\gamma-1}{\gamma}\cdot\frac{\rho_{lp}c_p T_{op}J}{P_{op}}\right)^{\gamma-1}\right]}+\right.$$

$$\left.\alpha_E\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{op}}{T_a}\right)\sqrt{2\,g\,c_p T_a J\left[1-\left(\frac{P_{op}}{P_a}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{\gamma-1}{\gamma}\cdot\frac{\rho_{lp}c_p T_{op}J}{P_{op}}\right)^{\gamma-1}\right]}\right\}V_2^2+$$

$$(\alpha_E+1)\frac{\gamma}{\gamma-1}P_a V_2-\rho_{lp}c_p T_{op}J\left\{\sqrt{2\,g\,c_p T_{op}J\left[1-\left(\frac{\gamma-1}{\gamma}\cdot\frac{\rho_{lp}c_p T_{op}J}{P_{op}}\right)^{\gamma-1}\right]}+\right.$$

$$\left.\alpha_E\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\sqrt{2\,g\,c_p T_a J\left[1-\left(\frac{P_{op}}{P_a}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{\gamma-1}{\gamma}\cdot\frac{\rho_{lp}c_p T_{op}J}{P_{op}}\right)^{\gamma-1}\right]}\right\}=0$$

$$\dots(155)$$

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The two nonlinear equations, (154) and (155), are solved for the two unknowns ρ_{1p} and V_2 in terms of dimensional input values of P_a, P_{op}, T_a, and T_{op}. The solution of these two equations, designated as ψ_1 and ψ_2, respectively, is obtained using the Newton-Raphson iteration procedure and Taylor's series as follows:

$$(\rho_{1p})_{i+1} = (\rho_{1p})_i + (h)_i \tag{156}$$

$$(V_2)_{i+1} = (V_2)_i + (k)_i \tag{157}$$

where $i = 0, 1, 2 \ldots$ representing successive iterations. Using Taylor's series, the functions $(\psi_1)_{i+1}$ and $(\psi_2)_{i+1}$ can be expressed as follows:

$$(\psi_1)_{i+1} = (\psi_1)_i + (h)_i \left(\frac{\partial \psi_1}{\partial \rho_{1p}}\right)_i + (k)_i \left(\frac{\partial \psi_1}{\partial V_2}\right)_i \tag{158}$$

$$(\psi_2)_{i+1} = (\psi_2)_i + (h)_i \left(\frac{\partial \psi_2}{\partial \rho_{1p}}\right)_i + (k)_i \left(\frac{\partial \psi_2}{\partial V_2}\right)_i \tag{159}$$

Solving for $(h)_i$ and $(k)_i$ from equations (158) and (159) yields

$$(h)_i = \frac{\begin{vmatrix} -\psi_1 & \dfrac{\partial \psi_1}{\partial V_2} \\[2ex] -\psi_2 & \dfrac{\partial \psi_2}{\partial V_2} \end{vmatrix}_i}{\begin{vmatrix} \dfrac{\partial \psi_1}{\partial \rho_{1p}} & \dfrac{\partial \psi_1}{\partial V_2} \\[2ex] \dfrac{\partial \psi_2}{\partial \rho_{1p}} & \dfrac{\partial \psi_2}{\partial V_2} \end{vmatrix}_i} \tag{160}$$

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$$(k)_i = \cfrac{\begin{vmatrix} \dfrac{\partial \psi_1}{\partial \rho_{1p}} & -\psi_1 \\[2ex] \dfrac{\partial \psi_2}{\partial \rho_{1p}} & -\psi_2 \end{vmatrix}_i}{\begin{vmatrix} \dfrac{\partial \psi_1}{\partial \rho_{1p}} & \dfrac{\partial \psi_1}{\partial V_2} \\[2ex] \dfrac{\partial \psi_2}{\partial \rho_{1p}} & \dfrac{\partial \psi_2}{\partial V_2} \end{vmatrix}_i} \tag{161}$$

The above iteration procedure is started assuming initial conditions $(i = 0)$

$$(\rho_{1p})_0 = K_1 \rho_{ap} \tag{162}$$

$$(V_2)_0 = K_2 V_{ap} \tag{163}$$

where K_1 and K_2 are suitable programmed constants and ρ_{ap} and V_{ap} are obtained from equations (71) and (72), respectively.

A simplified flow diagram of this computer program is shown in Figure 25, and a typical sample of final output is presented in Table XV.
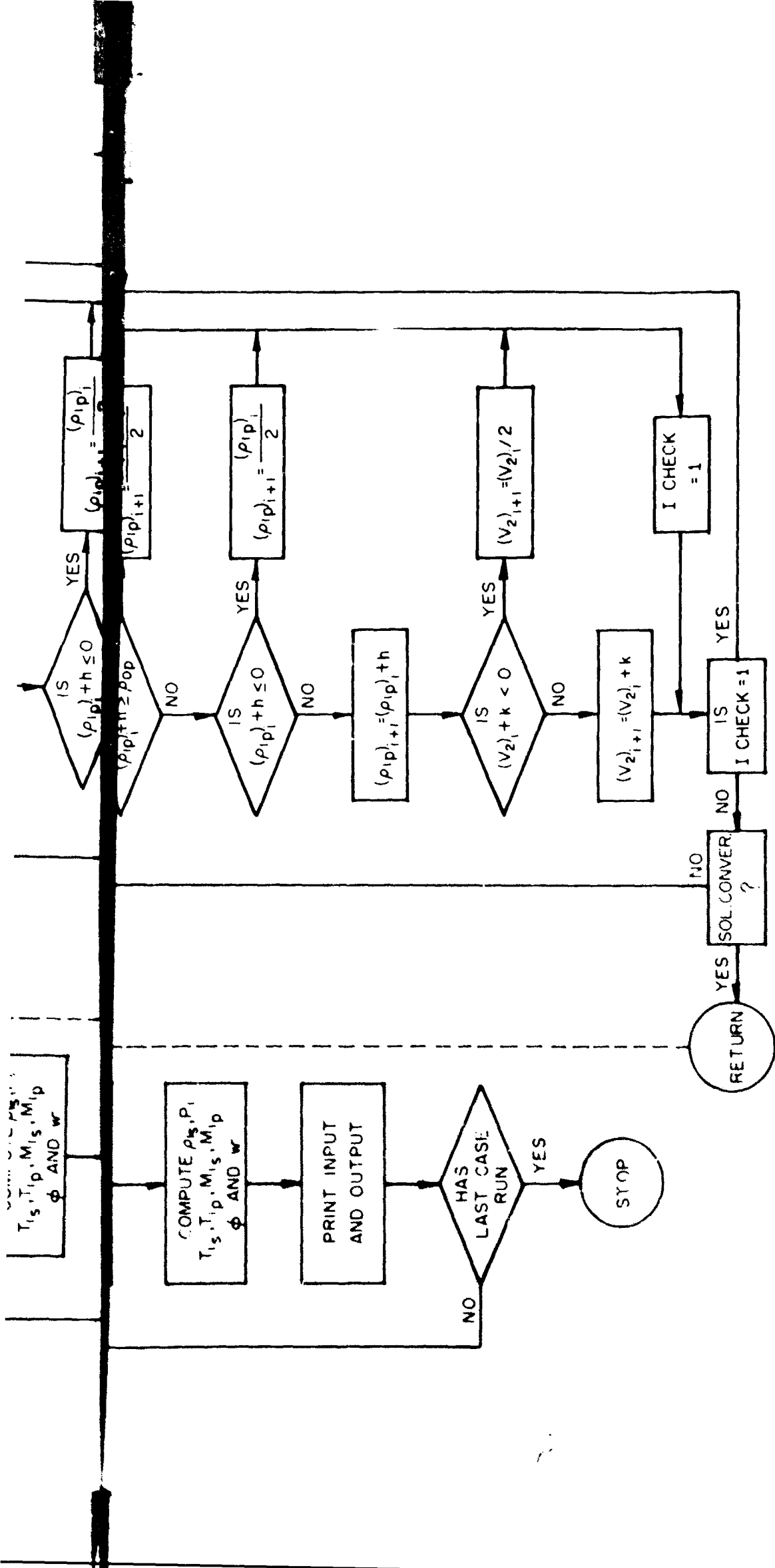
Figure 25. Computer Flow Diagram for Compressible Flow Analysis.

TABLE XV

TYPICAL COMPUTER RESULTS FOR COMPRESSIBLE ANALYSIS

AIR TEMP	STAG TEMP	V-INF	GAMMA	SPEC HEAT
0.53000E 03	0.14600E 04	0.0	0.14000E 01	0.24100E 00

AMB PRESSURE 0.2?00E 04
TOTAL PRESSURE 0.36000E 04

PRIMARY JET TO AMBIENT
RHO(AP)= 0.4?38E-01 T(AP)= 0.4108E 03 V(AP)= 0.13422E 04 MACH NO.= 0.9050E 00

PRIMARY JET IN MIXING CHAMBER

ALPHA	DENSITY	PRESSURE	TEMPERATURE	VELOCITY	MACH NO.
0.50000E-02	0.4273E-01	0.20724E 04	0.1052E 03	0.13568E 04	0.9244E 00
0.10000E-01	0.4228E-01	0.20382E 04	0.909989E 03	0.13856E 04	0.9393E 00
0.50000E-01	0.3967E-01	0.18676E 04	0.8787E 03	0.14793E 04	0.1015E 01
0.10000E 00	0.384?E-01	0.17856E 04	0.8675E 03	0.15243E 04	0.1057E 01
0.20000E 00	0.3803E-01	0.17607E 04	0.2441E 03	0.15380E 04	0.1054E 01
0.50000E 00	0.3835E-01	0.17811E 04	0.8569E 03	0.15269E 04	0.1055E 01
0.10000E 01	0.3809E-01	0.18214E 04	0.8725E 03	0.15046E 04	0.1036E 01
0.20000E 01	0.3919E-01	0.18773E 04	0.8800E 03	0.14739E 04	0.1010E 01
0.50000E 01	0.4104E-01	0.19584E 04	0.8907E 03	0.14294E 04	0.9746E 00
0.10000E 02	0.4183E-01	0.20115E 04	0.8979E 03	0.14080E 04	0.9513E 00
0.50000E 02	0.4291E-01	0.20847E 04	0.9068E 03	0.13961E 04	0.9191E 00
0.10000E 03	0.4312E-01	0.20989E 04	0.9085E 03	0.13955E 04	0.9113E 00

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TABLE XV (CONTINUED)

SECONDARY JET IN MIXING CHAMBER

ALPHA	DENSITY	PRESSURE	TEMPERATURE	VELOCITY	MACH NO.
0.50000E-02	0.734369E-01	0.207242E 04	0.526788E 03	0.196959E 03	0.174624E 00
0.10000E-01	0.725688E-01	0.203821E 04	0.524289E 03	0.262618E 03	0.233391E 00
0.50000E-01	0.681766E-01	0.186762E 04	0.511357E 03	0.474458E 03	0.426953E 00
0.10000E 00	0.660256E-01	0.178565E 04	0.504842E 03	0.551165E 03	0.499170E 00
0.20000E 00	0.653676E-01	0.176078E 04	0.502823E 03	0.572858E 03	0.519857E 00
0.50000E 00	0.659063E-01	0.178113E 04	0.504477E 03	0.555156E 03	0.502966E 00
0.10000E 01	0.669685E-01	0.182145E 04	0.507713E 03	0.518763E 03	0.468494E 00
0.20000E 01	0.684302E-01	0.187735E 04	0.512117E 03	0.464690E 03	0.417853E 00
0.50000E 01	0.705293E-01	0.195847E 04	0.518344E 03	0.375167E 03	0.335320E 00
0.10000E 02	0.718902E-01	0.201157E 04	0.522322E 03	0.304506E 03	0.271126E 00
0.50000E 02	0.737490E-01	0.208477E 04	0.527683E 03	0.167302E 03	0.112284E 00
0.10000E 03	0.741076E-01	0.209897E 04	0.528707E 03	0.124968E 03	0.105095E 00

TABLE XV (CONTINUED)

MIXED FLOW AFTER EXIT FROM MIXING CHAMBER (NO DIFFUSER)

ALPHA	DENSITY	TEMPERATURE	VELOCITY	MACH NO.
0.50000E-02	0.434028E-01	0.910489E 03	0.134068E 04	0.904133E 00
0.10000E-01	0.434289E-01	0.909943E 03	0.133834E 04	0.902828E 00
0.50000E-01	0.437573E-01	0.903114E 03	0.131254E 04	0.888762E 00
0.10000E 00	0.442239E-01	0.893584E 03	0.127871E 04	0.870456E 00
0.20000E 00	0.450804E-01	0.876607E 03	0.121988E 04	0.838415E 00
0.50000E 00	0.472450E-01	0.836443E 03	0.108440E 04	0.762985E 00
0.10000E 01	0.499867E-01	0.790566E 03	0.934007E 03	0.675967E 00
0.20000E 01	0.536516E-01	0.736563E 03	0.759784E 03	0.569678E 00
0.50000E 01	0.590884E-01	0.668791E 03	0.538652E 03	0.423845E 00
0.10000E 02	0.628716E-01	0.628547E 03	0.401234E 03	0.325666E 00
0.50000E 02	0.689797E-01	0.572890E 03	0.191952E 03	0.163193E 00
0.10000E 03	0.705888E-01	0.559831E 03	0.138077E 03	0.118751E 00

TABLE XV (CONCLUDED)

ALPHA	PHI	ENT. RATIO	NO OF ITERATIONS
0.50000E-02	0.100307E 01	0.123819E-02	2
0.10000E-01	0.100515E 01	0.325701E-02	2
0.50000E-01	0.101265E 01	0.275586E-01	5
0.10000E 00	0.101762E 01	0.621375E-01	5
0.20000E 00	0.102991E 01	0.128017E 00	5
0.50000E 00	0.106616E 01	0.312428E 00	5
0.10000E 01	0.111579E 01	0.592491E 00	4
0.20000E 01	0.118872E 01	0.108356E 01	4
0.50000E 01	0.131603E 01	0.225511E 01	4
0.10000E 02	0.142442E 01	0.373700E 01	3
0.50000E 02	0.165834E 01	0.105701E 02	3
0.10000E 03	0.173899E 01	0.158825E 02	5

APPENDIX II

BIBLIOGRAPHY

Presented in this Appendix is a compilation of a total of 585 technical reports on the state of the art of jet ejectors. For convenience, the papers are arranged in an alphabetical order by authors. A portion of the technical reports presented herein are discussed in Section III of this report. The following constitutes a fairly complete bibliography on jet ejectors:

Abramovich, G. N., Turbulent Jets Theory (Translation), MCL-1256/1+2, Technical Documents Liaison Office, MCLTD, Wright-Patterson Air Force Base, Ohio, August 1962.

Acharya, Y. V. G., Momentum Transfer and Heat Diffusion in the Mixing of Coaxial Turbulent Jets Surrounded by a Pipe, Thesis (Dr.) Netherlands Techs. Hoogeschool, Delft, The Netherlands, 1954.

Acharya, Y. V. G., "The Design of a Cylindrical Injector", Applied Science Reviews, Section A, Volume 5.

Ackeret, J., High-Speed Wind Tunnels, TM 808, NACA, November 1936.

Addy, A. L., On the Steady State and Transient Operating Characteristics of Long Cylindrical Shroud Supersonic Ejectors (with Emphasis on the Viscous Interaction Between the Primary and Secondary Streams), Thesis (Ph.d.), University of Illinois, Urbana, Illinois, CR-56653, NASA, 1963.

Addy, A. L., "Transient Pumping Characteristics of Supersonic Ejector System of Rocket Engine Exhaust Stream", Journal of Basic Engineering, Trans. ASME, 1964.

Addy, A. L., and Chow, W. L., On the Starting Characteristics of Supersonic Ejector Systems, Paper 64-FE-9, ASME, February 1964.

Ahren, B., "Note on the Cylindrical Ejector Supersonic
Propelling Nozzle", Journal of the Royal Aeronautical
Society, Volume 67, October 1963, pp. 670-671.

Akhmedov, R. B., Gorbanenko, A. D., Zharkov, B. L., and
Tsirulnikov, L. M., Discharge Coefficient of Swirl
Injectors, TT F-9726, NASA, October 1965.

Alexander, L. G., A Bibliography on Free and Ducted Turbulent
Jets, Technical Report No. 14, University of Illinois,
Engineering Experimental Station, Urbana, Illinois,
August 1952.

Alexander, L. G., Transport of Momentum, Mass and Energy in
the Jet Ejector, University of Illinois, Engineering
Experimental Station, Urbana, Illinois.

Alexander, L. G., Baron, T., and Comings, E. W., Transport of
Momentum, Mass and Heat in Turbulent Jets, Technical
Report No. 8, University of Illinois, Engineering Experi-
mental Station, Urbana, Illinois, September 1950
(corrected May 1951).

Alexander, L. G., Comings, E. W., Grimmett, H. L., and
White, E. A., Transfer of Momentum in Jet of Air Issuing
into a Tube, Technical Report No. 11, University of
Illinois, Engineering Experimental Station, Urbana,
Illinois, May 1952.

Alexander, L. G., and Kivnick, A., Simultaneous Transport of
Energy and Momentum in a Ducted Jet, Technical Report
No. 12, University of Illinois, Engineering Experimental
Station, Urbana, Illinois, 1952.

Alexander, L. G., Kivnick, A., Comings, E., and Henze, E. D.,
"Transport of Momentum and Energy in a Ducted Jet",
American Institute of Chemical Engineering Journal,
1:55-61, March 1955.

Alexander, L. G., Kivnick, A., Comings, E., and Henze, E. D.,
"Experimental Study of a Non-Isothermal Jet of Air
Discharging into a Duct", American Institute of Chemical
Engineers Journal, 1:55-61, March 1955.

Allen, J. L., Pumping Characteristics for Several Simulated Variable-Geometry Ejectors with Hot and Cold Primary Flow, RM E54G15, NACA, September 1954.

Alvermann, W., Theoretical Thrust Increase Through Gas Dynamic Mixing (in German), DFL-Bericht Nr. 181, Deutsche Forschungsanstalt fuer Luft- und Ramfahrt E. V., Braunschweig, Germany, 1962.

Alvermann, W., and Lambrecht, J., Mathematical Treatment of the Mixture of Two Gas Jets of Various Temperature and Velocity (Translation), F-TS-10103/III, Air Technical Intelligence Center, Wright-Patterson Air Force Base, Ohio, December 1954.

Anderson, S. B., Faye, A. E., Jr., and Innis, R. C., Flight Investigation of the Low-Speed Characteristics of a 35° Swept-Wing Airplane Equipped with an Area-Suction Ejector Flap and Various Wing Leading-Edge Devices, RM A57G10, NACA, September 1957.

Anon., Analytical and Experimental Evaluation of Ejectors with 90-Degree Turns, Report No. 2403, Aerojet-General Corporation, Sacramento, California, November 1962.

Anon., "Ejectors and Boosters", ASME Power Test Code PTC 24, 1956.

Anon., The Possibilities of Jet Ejectors, Memorandum KR/65, Bristol Airplane Company, Ltd., Engine Division, February 1944.

Anon., Performance of a Jet Pipe Ejector with Convergent Divergent Nozzle, Bristol Siddeley Engine Company.

Anon., A Theoretical and Experimental Investigation of Flow Induction Systems Applicable to Wind Tunnels, Report No. AD-526-A-1, Cornell Aeronautical Laboratory Inc., Buffalo, New York, February 1948.

Anon., A Contribution to the Theory of Thrust (Momentum) Augmentors, Report 197-2, Frost Engineering Development Corporation, Englewood, Colorado, August 1963.

Anon., Use of Ejectors at the Jet Nozzle to Improve Cooling of Gas Turbine Installation, Bulletin No. DF 81374, General Electric Company, Aircraft Gas Turbine Engineering Division, Schenectady, New York.

Anon., Thrust Augmentation of Several Annular Nozzle Ejectors as Determined by Model Tests, Report ARD-222, Hiller Aircraft Corporation, Propulsion and Preliminary Design Department, Palo Alto, California, 1959.

Anon., "Concerning a Simple Property for Optimum Adaptation of Supersonic Ejectors" (in French), La Recherche Aeronautique, March-April 1956, p. 27.

Anon., Recirculation Principle for Ground Effect Machines 2-D Tests, OR-2073, Martin Corporation, Orlando, Florida, January 1962.

Anon., Recirculation Principle for Ground Effect Machines. Basic Two-Dimensional Experimental Data, OR 2496, Martin Company, Orlando, Florida, January 1962.

Anon., The Thrust from Multi-Ejectors, DOR/PRSN1/FEB, Rolls-Royce Limited, Experimental Department, April 1941.

Anon., A Preliminary Investigation of the Application of Ejector Pumps to the Ram Jet Addition Exhauster System, Report No. R 887-12-2, Sverdrup and Parcel, Incorporated, May 1951.

Anon., Pumping Tests, Ejector Cooling Development, Thorp Engineering Company, September 1957.

Antonovich, S. A., Design of Jet Pumps (Ejectors) (Translation), FTD-TT-62-449/1+2, Air Force Systems Command, Foreign Technology Division, Wright-Patterson Air Force Base, Ohio, July 1962.

Arkadov, Y. K., Gas Ejector (Translation), FTD-TT-1782/1+2+4, Air Force Systems Command, Foreign Technology Division, Wright-Patterson Air Force Base, Ohio, February 1966.

Arkadov, Y. K., Gas Ejector (Translation), FTD-TT-65-
1783/1+2+4, Air Force Systems Command, Foreign Technology
Division, Wright-Patterson Air Force Base, Ohio,
February 1966.

Armstrong, H. C., "The Principle of Injector Burners for
Either Gas-Air or Air-Gas Mixtures", Gas World, 118 (3061),
1943, pp. 43-53.

Arnberg, B. T., Operating Characteristics of Jet Pumps Using
Gaseous Primary and Secondary Streams, University of
Colorado, Engineering Experiment Station, Boulder,
Colorado, April 1958.

Ashwood, P. F., Crosse, G. W., and Goddard, J. E., Measure-
ments of the Thrust Produced by Convergent-Divergent
Nozzles at Pressure Ratios up to 20, Memorandum No. M 288,
National Gas Turbine Estab_Lishment, Pyestock, Britain,
November 1956.

Bailey, A., An Investigation of the Principles of the Air
Ejector, Technical Report 1545, Aeronautical Research
Committee, London, Britain, 1933.

Bailey, A., and Wood, S. A., High Speed Induced Wind Tunnel,
R. & M. No. 1468, Aeronautical Research Commit'ee, London,
Britain, May 1932.

Bailey, A., and Wood, S. A., An Investigation of the
Principles of the Air Injector, R. & M. No. 1545, Aero-
nautical Research Council, London, Britain, February 1933.

Bailey, A., and Wood, S. A., The Development of a High Speed
Induced Wind Tunnel of Rectangular Cross Section, R. & M.
No. 1791, Aeronautical Research Council, London, Britain,
February 1937.

Bailey, A., and Wood, S. A., Further Development of a High
Speed Wind Tunnel of Rectangular Cross Section, R. & M.
No. 1853, Aeronautical Research Council, London, Britain,
September 1938.

141

Barningham, R. C., Component Propulsion Program for Future
  High-Performance Strategic Aircraft, Volume XII,
  Augmenters, PWA-2767-Volume 12, Pratt & Whitney Aircraft,
  East Hartford, Connecticut, February 1966.

Barton, D. L., and Taylor, D., An Investigation of Ejectors
  without Induced Flow, Phase I, AEDC-TN-59-145, Arnold
  Air Force Station, Tennessee, December 1959.

Bauer, R. C., Characteristics of Axisymmetric and Two-
  Dimensional Isoenergetic Jet Mixing Zones, AEDC-TR-63-253,
  Arnold Engineering Development Center, Arnold Air Force
  Station, Tennessee, December 1963.

Bauer, R. C., Theoretical Base Pressure Analysis of Axi-
  symmetric Ejectors without Induced Flow, AEDC-TDR-64-3,
  Arnold Engineering Development Center, Arnold Air Force
  Station, Tennessee, January 1964.

Bauer, R. C., and German, R. C., Some Reynolds Number Effects
  on the Performance of Ejectors without Induced Flow,
  AEDC-TN-61-87, Arnold Engineering Development Center,
  Arnold Air Force Station, Tennessee, August 1961.

Bauer, R. C., and German, R. C., The Effect of Second Throat
  Geometry on the Performance of Ejectors without Induced
  Flow, AEDC-TN-61-133, Arnold Engineering Development
  Center, Arnold Air Force Station, Tennessee, November 1961.

Baulin, K., Air-Jet Blowers (Ejectors), ARC 2850, 1935

Bauman, J. A., Tests of DD828 Main Air Ejector Submitted by
  Foster Wheeler Corporation, Report C-3812, Naval
  Engineering Experimental Station, Annapolis, Maryland,
  March 1950.

Bean, D. R., "Note on the Theory of the Steam Ejector",
  Engineer, Volume 180, No. 4675, August 1945, pp. 131-132.

Barningham, R. C., Component Propulsion Program for Future
  High-Performance Strategic Aircraft, Volume XII,
  Augmenters, PWA-2767-Volume 12, Pratt & Whitney Aircraft,
  East Hartford, Connecticut, February 1966.

Barton, D. L., and Taylor, D., An Investigation of Ejectors without Induced Flow, Phase I, AEDC-TN-59-145, Arnold Air Force Station, Tennessee, December 1959.

Bauer, R. C., Characteristics of Axisymmetric and Two-Dimensional Isoenergetic Jet Mixing Zones, AEDC-TR-63-253, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, December 1963.

Bauer, R. C., Theoretical Base Pressure Analysis of Axisymmetric Ejectors without Induced Flow, AEDC-TDR-64-3, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, January 1964.

Bauer, R. C., and German, R. C., Some Reynolds Number Effects on the Performance of Ejectors without Induced Flow, AEDC-TN-61-87, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, August 1961.

Bauer, R. C., and German, R. C., The Effect of Second Throat Geometry on the Performance of Ejectors without Induced Flow, AEDC-TN-61-133, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, November 1961.

Baulin, K., Air-Jet Blowers (Ejectors), ARC 2850, 1935.

Bauman, J. A., Tests of DD828 Main Air Ejector Submitted by Foster Wheeler Corporation, Report C-3812, Naval Engineering Experimental Station, Annapolis, Maryland, March 1950.

Bean, D. R., "Note on the Theory of the Steam Ejector", Engineer, Volume 180, No. 4675, August 1945, pp. 131-132.

Beeton, A. B. P., A Theoretical Calculation of the Reduction in Drag Obtainable by Ejector Action of the Exhaust Gases when Mixed with the Cooling Air-Flow of a Typical Air-Cooled Engine, R. & M. No. 2302, Aeronautical Research Council, London, Britain, April 1945.

Beheim, M. A., Off-Design Performance of Divergent Ejectors, RM E58G10A, NACA, September 1958.

143

Beke, A., and Simon, P. C., <u>Thrust and Drag Characteristics of Simulated Variable-Shroud Nozzles with Hot and Cold Primary Flows at Subsonic and Supersonic Speeds</u>, RM E54J26, NACA, February 1955.

Belter, R. H., <u>Theoretical Performance of the Heated Jet Pump</u> Thesis (M.S.), United States Naval Postgraduate School, Monterey, California, 1963.

Benton, E. D., and Engdhahl, R. B., "Steam-Air Jets for Abatement of Locomotive Smoke", <u>Trans. A.S.M.E.</u>, 69, 35, 1947.

Berry, J. R., and Irving, D. E., <u>Application of Jet Augmentation to Turbine Supercharger Installations</u>, Memorandum Report, U. S. Army Air Force Materiel Command, Engineering Division, March 1944.

Bertin, J., "Dilution Pulsatoire sur Reacteur", C. R. Academy of Science, Paris, 1955, p. 1859.

Bertin, J., "Les Trompes Appliquées au Vol Vertical vers l'Aile-Trompe", <u>Technique et Sciences Aeronautiques</u>, Tome 2, 1960.

Bertin, J., <u>Ejectors (General Studies, Annular Ejectors and Ejector Wings)</u>, Note Tech. 4-3, 4-4, 4-23, 4-27, 4-32, 4-48, 4-51, 10-5, 10-0, 16-27, 16-30.

Bertin, J., and LeNabour, M., "Les Trompes au service de l'Aviation", <u>Bulletin Technique du Bureau Veritas</u>, 41e Annee, No. 9, September 1959, pp. 567-573.

Bertin, J., and le Nabour, M., <u>Contribution to the Development of Ducts and Ejectors (Translation)</u>, Technical Translation NRC TT-976, National Research Council, Ottawa, Canada, 1961.

Bertin, J., and le Nabour, M., "Contribution au Developement des Trompes et Ejecteurs", <u>Technique et Sciences Aeronautiques</u>, Tome 3, May-June 1959, pp. 127-138.

Bertin et Cie, Ejectors on Jet Apparatus, UK Patent, Spec. 861519, February 1961.

Bidwell, J. M., Analysis of an Induction Blowdown Supersonic Tunnel, TN 2040, NACA, April 1950.

Black, J., "A Note on the Mixing Process in the Flow Induced by a High Velocity Air Jet", Journal of the Royal Aeronautical Society, Volume 61, No. 9, September 1957, pp. 631-633.

Bloomer, H. E., Experimental Results of an Investigation of Two Methods of Inflight Thrust Measurement Applicable to Afterburning Turbojet Engines wi`` Ejectors, RM E57H28, NACA, May 1958.

Bock, G., and Spintzyk, H., VTOL-STOL Aircraft, Bibliography 2 (Revised Edition), Advisor Group for Aeronautical Research and Development, NATO, Paris, France, March 1961.

Bonnington, S. T., The Design of Ejectors Driven by and Containing Compressible Fluids, TN 717, British Hydromechanical Research Association, February 1962.

Bonnington, S. T., "A Guide to Jet Pump Design", British Chemical Engineering, Volume 9, No. 3, March 1964, pp. 150-154.

Borisenko, A. I., Gasdynamics of Engines (Translation), FTD-TT-63-852/1·?, Air Force Systems Command, Foreign Technology Division, Wright-Patterson Air Force Base, Ohio, October 1964.

Bosnjakovic, F., "Über Dampfstrahlgeblase", Z. ges Kalteindustrie, Volume 46, 1936, p. 229.

Bradshaw, P., Preliminary Note on a Mixing Nozzle-Ejector Shroud Combination for Jet Noise Reduction, Aero Report No. 1116 (A.R.C. 26201), National Physical Laboratory, Britain, September 1964.

Burgers, J. M., and Ghaffari, A., On the Application of Steam Driven Water Jets for Propulsion, Report No. 5307, National Bureau of Standards, Washington, D. C., May 1957.

Burley, R. R., and Bryant, L., Experimental Investigation of Coaxial Jet Mixing of Two Subsonic Streams at Various Temperatures, Mach Numbers, and Diameter Ratios for Three Configurations, Memo 12-21-58 E, NASA, February 1959.

Busemann, A., Increase of Thrust by Admixture of Air (in German), Lilienthal-Gesellschaft fuer Luftfahrtfarschung, Bericht 118, 1938.

Busemann, A., Schriften der Deutschen Akademie fuer Luftfahrtforschung, Heft 1071/43, Berlin, 1943.

Callagan, E. E., and Coles, W. D., Experimental Investigation of Effect of Jet Exit Configuration on Thrust and Drag, RM E51J22, NACA, December 1951.

Campbell, A. J., Investigation of a Wide Angle Diffuser with Air Augmentation for Use as a Jet Muffler, UTIA Technical Note No. 15, University of Toronto, Institute of Aerophysics, Toronto, Canada, August 1957.

Campbell, P. J., Ground Tests of Exhaust Gas Thrust Augmenters, Report R-50, United Aircraft Corporation, Research Division, East Hartford, Connecticut, November 1940.

Carriere, P., "Effet d'une injection de fluide dans l'eau morte sur les conditions de recollement d'un écoulement plan supersonique, t. 251, C.R. Ac. des Sciences, Paris, France, December 1960, pp. 2877-2879.

Carriere, P., and Sirieux, M., Facteurs d'influence du recollement d'un ecoulement supersonique, Communication à Stresa, O.N.E.R.A., Paris, France.

Carter, D. J., Jr., and Vick, A. R., Experimental Investigation of Axial and Normal Force Characteristics of Skewed Nozzles, TN 4336, NACA, September 1958.

Carter, P. B., Jr., Capability and Cost Study for Component and Model Test Facility. Phase II, Supplement 3, Optimization of Certain Ejector Design Parameters, AEDC-TR-65-141, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, July 1965.

146

Carter, P. B., Jr., <u>Capability and Cost Study for Component and Model Test Facility, Phase III, Supplement 5, Off-Design Performance of the Component and Model Test Facility Exhaust System</u>, AEDC-TR-65-143, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, August 1965.

Carter, P. B., Jr., and Moger, W. C., <u>Capability and Cost Study for Component and Model Test Facility, Phase III, Supplement 4, Analytical Method and Computer Program for Off-Design Performance Evaluation of Multi-stage Gas-Driven Ejector Systems with Interstage Cooling</u>, AEDC-TR-65-142, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, July 1965.

Chalom, J., "Sur les trompes à réaction", <u>CR Acad. Sci.</u>, Paris, France, Volume 199, 1934, pp. 1289-1291.

Chalom, J., "Sur les trompes à réaction", <u>CR Acad. Sci.</u>, Paris, France, Volume 202, 1936, pp. 1751-1753.

Chalom, J., "Sur les trompes à réaction à écoulement supersonique", <u>CR Acad. Sci.</u>, Paris, France, Volume 204, 1937, pp. 1614-1615.

Chalom, J., "Sur l'augmentation maximum du quantité de mouvement réalisable à l'aide d'une trompe au point fixe", <u>CR Acad. Sci.</u>, Paris, France, Volume 222, 1946, pp. 1028-1030.

Chaulin, P., and Sandre, P., <u>Turbofan-Ramjet Engine Studies, Volume VI-Exit Flow Interaction Studies</u>, Technical Report AFAPL-TR-66-33, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, May 1964.

Cherkez, A. Ya., "Certain Properties of Supersonic Flow in the Initial Section of a Gas Ejector", <u>Mechanics and Machine Construction (Selected Articles)</u> (Translation), FTD-TT-63-375/1+2+4, Air Force Systems Command, Foreign Technology Division, Wright-Patterson Air Force Base, Ohio, June 1963, pp. 12-32.

147

Chevallier, J. P., and Jousserandot, P., <u>Adaptation of Jet Pumps for Combined Suction and Blowing on an Airplane Wing</u> (Translation), Engineering Study N.. 126, University of Wichita, Wichita, Kansas, December 1953.

Chisholm, R. G. A., <u>Design and Calibration of an Air Ejector to Operate Against Various Back Pressures</u>, UTIA Tech. Note 39, University of Toronto, Institute of Aerophysics, Toronto, Canada, September 1960.

Chow, W. L., and Addy, A. L., "Interaction between Primary and Secondary Streams of Supersonic Ejector Systems and Their Performance Characteristics", <u>AIAA Journal</u>, Volume 2, No. 4, April 1964, pp. 686-695.

Chow, W. L., and Yeh, P. S., "Characteristics of Supersonic Ejector Systems with Nonconstant Area Shroud", <u>AIAA Journal</u>, Volume 3, No. 3, March 1965, pp. 525-527.

Christianovich, S. A., <u>Ejector Design</u> (in Russian), Industrial Aerodynamics, Office of Modern Engineering, NKAP, 1944.

Christianson, M., <u>Experimental Evaluation of an Axial-Flow Vaneless Compressor Designed for Thrust Augmentation</u>, Report D211172-1, United Aircraft Corporation, Research Laboratory, East Hartford, Connecticut, April 1965.

Christianson, M., <u>Experimental Evaluation of a Jet-Reaction Driven Fan</u>, Report UAR-D80, United Aircraft Corporation, Research Laboratory, East Hartford, Connecticut, June 1965.

Ciepluch, C. C., and Fenn, D. B., <u>Experimental Data for Four Full-Scale Conical Cooling-Air Ejectors</u>, RM E54F02, NACA, November 1954.

Ciepluch, C. C., North, W. J., Coles, W. D., and Antl, R. J., <u>Acoustic, Thrust and Drag Characteristics of Several Full-Scale Noise Suppressors for Turbojet Engines</u>, TN 4261, NACA, April 1958.

Ciolkosz, Z. M., VTOL Jet-Supported Aircraft with Thrust Augmentation and Jet Noise, Velocity and Temperature Reduction, Hiller Aircraft Corporation, Advanced Research Division, July 1959 (Revised September 1959).

Citrini, D., A Contribution to Jet-Pump Design, TT F-9263, NASA, February 1965.

Codegone, C., Ejectors with Supersonic Exhaust Velocities (Translation), Library Translation No. 430, Royal Aircraft Establishment, Farnborough, Britain, July 1953.

Codegone, C., "Experienze su eiettori", Termotecnia, Volume 13, No. 10, October 1959, pp. 481-495.

Coles, W. D., Mihaloew, J. A., and Callagan, E. E., Turbojet Engine Noise Reduction with Mixing Nozzle-Ejector Combinations, TN 4317, NACA, August 1958.

Coles, W. D., Mihaloew, J. A., and Swann, W. H., Ground and In-Flight Acoustic and Performance Characteristics of Jet-Aircraft Exhaust Noise Suppressors, TN D-874, NASA, August 1961.

Cox, P. B., and Campbell, J. R., Phase I Summary Technical Report on Advanced Engine Studies, Report 25,080, Volume 2, Marquardt Corporation, Van Nuys, California, 1963.

Crabtree, D. L., Investigation of the Influence of the Design Parameters on the Flow Characteristics of the Drive Nozzle of a Gas-Driven Jet Pump, Thesis (M.S.), Purdue University, Lafayette, Indiana, 1961.

Crabtree, D. L., Investigation of a Gas-Driven Jet Pump for Rocket Engines, Report No. F-62-1, Purdue University, Lafayette, Indiana, January 1962.

Cramp, L. G., "A Cold Turbine Ejector Design", Aeronautics, Volume 41, No. 4, February 1960, pp. 38-39.

Crocco, L., High-Speed Wind Tunnels, Translation No. 366, Headquarters Air Materiel Command, Wright Field, Dayton, Ohio, July 1943.

149

Crocco, L., "One-Dimensional Treatment of Steady Gas
   Dynamics", _Fundamentals of Gas Dynamics, High Speed
   Aerodynamics and Jet Propulsion_, Volume III (Emmons, H. E.,
   Editor), Princeton University Press, Princeton,
   New Jersey, 1958, Sec. B., p. 291.

Croft, T., "Practical Information About Injectors", _Power_,
   Volume 55, 1922, pp. 460-463.

Cruse, R. E., and Tontini, R., _Research on Coaxial Jet
   Mixing_, Report GB/C 62-354A, General Dynamics/Convair,
   San Diego, California, November 1962.

Cubbage, J. M., Jr., _Effect of Convergent Ejector Nozzles
   on the Boattail Drag of a 16° Conical Afterbody at Mach
   Numbers of 0.6 to 1.26_, RM L58G25, NACA, September 1955.

Curry, R., _Experimental Study of Ejectors for Use in
   Exhausting Ram-Jet Test Burners_, Meteor Report UAC-32,
   United Aircraft Corporation, Research Department,
   East Hartford, Connecticut, January 1949.

Curtet, R., "Contribution expérimentale à l'étude d'une
   trompe à liquides", _CR Acad. Sci. Paris_, Volume 236,
   1953, pp. 1134-1136.

Curtet, R., "Quelques aspects de l'écoulement dans une
   trompe à liquides", _CR Acad. Sci. Paris_, Volume 239,
   1954, np. 387-388.

Curtet, R., "Etude experimentale de la periode du jet
   inducteur dans une trompe a liquides", _CR Acad. Sci.
   Paris_, Volume 239, 1964, pp. 472-474.

Curtet, R., _Jet Flow Between Walls. Detailed Study of
   Ejector Pumps_ (Translation), Report No. RSTC-461,
   Redstone Scientific Information Center, Redstone
   Arsenal, Alabama, September 1965.

David, L. J., Smith, F. H., Jr., and Carter, P. B.,
   _Capability and Cost Study for Component and Model Test
   Facility, Summary Report_, AEDC-TR-65-138, Arnold
   Engineering Development Center, Arnold Air Force Station,
   Tennessee, July 1965.

150

Dean, F. P., *A Small Injector for Use in Mixing Sprays*,
ET-217, U. S. Department of Agriculture, Bureau
Entomology Plant Quarantine, June 1944.

Deich, M. E., and Robozhev, A. V., *On the Problem of the
Limiting Regime of Jet Compressors* (in Russian), Nauchn,
Dokl, Vysshei Shkoly Energ. 1, 1959, pp. 175-180.

DeLeo, R. V., *An Experimental Investigation of the Use of
Hot Gas Ejectors for Boundary Layer Control, Part III*,
WADC Technical Report 52-128, Part III, Wright Air
Development Center, Wright-Patterson Air Force Base, Ohio,
June 1958.

DeLeo, R. V., and Hermann, R., *Report of Progress on Free
Jet and Ejector Studies*, AEDC-TR-55-46, Arnold Engineering
Development Center, Arnold Air Force Station, Tennessee,
December 1953.

DeLeo, R. V., and Rose, R. E., *An Experimental Investigation
of a Special Air Ejector for the Ram Jet Addition
Exhauster System of AEDC*, Research Report No. 112,
University of Minnesota, Minneapolis, Minnesota, March 1955.

DeLeo, R. V., and Rose, R. E., *An Experimental Investigation
of the Use of Supersonic Driving Jets for Ejector Pumps*,
WADC Technical Report 57-357, Wright Air Development Center,
Wright-Patterson Air Force Base, Ohio, December 1958.

DeLeo, R. V., and Wood, R. D., *An Experimental Investigation
of the Use of Hot Gas Ejectors for Boundary Layer Removal*,
WADC Technical Report 52-128, Part I, Wright Air
Development Center, Wright-Patterson Air Force Base, Ohio,
April 1952.

DeLeo, R. D., and Wood, R. D., *An Experimental Investigation
of the Use of Hot Gas Ejectors for Boundary Layer Control*,
Part II, WADC Technical Report 52-128, Wright Air
Development Center, Wright-Patterson Air Force Base, Ohio,
December 1953.

Dennard, J. S., and Little, B. H., Jr., <u>Effects of Auxiliary and Ejector Pumping on the Mach Number Attainable in a 4½-by-4½-Inch Slotted Tunnel at Low Pressure Ratios</u>, RM L53K19, NACA, January 1954.

Deodati, J. B., and Monteath, E. B., <u>An Investigation of the Round Jet in a Moving Air Stream</u>, Thesis, California Institute of Technology, Guggenheim Aeronautical Laboratory, Pasadena, California, 1947.

d'Ews Thompson, T. A., and Chan, Y. Y., <u>An Ejector for a Hypersonic Wind Tunnel</u>, Aerodynamic Note 170, Australian Defence Scientific Service, Aeronautical Research Laboratories, Australia.

Deych, M. Y., <u>Technical Gas Dynamics</u> (Translation), FTD-TT-63-197, Air Force Systems Command, Foreign Technology Division, Wright-Patterson Air Force Base, Ohio, August 1964.

Dobrzelecki, A. J., <u>Efficiency Characteristics of a Recirculating Ejector</u>, Thesis (M.S.), Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, 1963.

Douchez, M., "Les Éjecteurs", <u>Inst. Tech. du Batiment et des Travaux Publics Annales</u>, Volume 12, No. 144, December 1959, pp. 1264-1277.

Dowson, R., "Performance of a Single Stage Steam Jet Operated Ejector", <u>Engineer</u>, Volume 164, 1937, pp. 650-680.

Drummond, A. M., and Gould, D. G., <u>Experimental Thrust Augmentation of a Variable Geometry, Two-Dimensional, Central Nozzle Ejector</u>, Report No. LR-328, National Research Laboratories, Ottawa, Canada, January 1962.

Dunham, J., "A Theory of the Cylindrical Ejector Supersonic Propelling Nozzle", <u>Journal of the Royal Aeronautical Society</u>, Volume 67, No. 625, January 1963, pp. 64-65.

DuPerow, J., and Bossart, E. B., <u>Design and Study of Steam Jets for Smoke Abatement</u>, Thesis (B.S.), Case School of Applied Science, Cleveland, Ohio, 1927.

Dyer, I., Franken, P. A., and Westervelt, P., "Jet Noise Reduction by Induced Flow", Journal of the Acoustical Society of America, Volume 30, No. 8, August 1958, p. 761.

Eastman, R. H., Effects of a Particle-Laden Driving Stream on Ejector Efficiency, Report No. 52, Joseph Kaye & Company, Cambridge, Massachusetts, March 1963.

Eichacker, S. S., and Hoge, H. J., "Jet-Compressor Efficiencies as Influenced by the Nature of the Driving and Driven Gases", Journal of the Aerospace Sciences, Volume 27, No. 8, August 1960, pp. 636 and 637.

Eichacker, S. S., and Hoge, H. J., Studies of Jet Compression II. Results with He, Air, CO_2, Freon-12, and Freon-113.

Eichelkraut, A. A., An Experimental Investigation of Ejector Thrust Augmentation, Thesis (M.S.), GA/ME/60-4, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, August 1960.

Eldred, K. M., White, R. W., Mann, M. A., and Cottis, M. G., Suppression of Jet Noise with Emphasis on the Near Field, Technical Documentary Report ASD-TDR-62-578, Air Force Systems Command, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, February 1963.

Ellerbrock, H. H., Jr., General Treatment of Compressible Flow in Ejectors and Example of Its Application to Problem of Effect of Ejector Addition on Thrust of Jet-Propulsion Units, RM L6L23, NACA, June 1947.

Elliott, D. G., Theoretical and Experimental Investigation of a Gas-Driven Jet Pump for Rocket Engines, Thesis (Ph.D.), Purdue University, Lafayette, Indiana, 1959.

Elliott, D. G., Investigation of a Gas-Driven Jet Pump for Rocket Engines, Technical Release No. 34-32, Jet Propulsion Laboratory, Pasadena, California, September 1960.

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Elliott, D. G., "Investigation of a Gas-Driven Jet Pump for Rocket Engines", <u>Progress in Astronautics</u>, Volume 2, Academic Press, New York, 1960.

Elliott, G. A., <u>An Experimental Study of Static Thrust Augmentation Using a Rocket-Ejector System</u>, Thesis (M.S.), Soughern Methodist University, Dallas, Texas, January 1964.

Ellis, C. W., <u>Pumping Action of Model Ejectors with Conical Mixing Sections</u>, NACA Conference on Cooling-Air Ejectors, Misc. A. G., 1948, pp. 6-9.

Ellis, C. W., Hollister, D. P., and Sargent, A. F., Jr., <u>Preliminary Investigation of Cooling-Air Ejector Performance at Pressure Ratio from 1 to 10</u>, RM E51H21, NACA, October 1951.

Ellis, C. W., Hollister, D. P., and Wilsted, H. D., <u>Investigation of Performance of Several Double-Shroud Ejectors and Effect of Variable-Area Exhaust Nozzle on Single Ejector Performance</u>, RM E52D25, NACA, July 1952.

Elrod, H. G., Jr., "The Theory of Ejectors", <u>Journal of Applied Mechanics, Trans. ASME</u>, Volume 12, September 1945, pp. A170-A174.

Evans, W. G., <u>Final Report on Exhaust Ejector Cooling Research</u>, Report No. 1703, AVCO Manufacturing Corporation, Lycoming Division, Stratford, Connecticut, August 1955.

Fabri, J., le Grives, F., and Siestrunck, R., "Etude aerodynamaque des trompes supersoniques", <u>Jahrbuch der Wissenschaftlichen Gesellschaft fuer Luftfahrt</u>, Braunschweig, Germany, 1953, pp. 101-110.

Fabri, J., and Paulon, J., <u>Theory and Experiments on Supersonic Air-to-Air Ejectors</u>, TM 1410, NACA, September 1958.

Fabri, J., and Siestrunck, R., "Supersonic Air Ejectors", <u>Advances in Applied Mechanics</u>, Volume V (Editors: Dryden, H. L., and von Karman, T.), The Academic Press Incorporated, New York, 1958, pp. 1-34.

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Fabri, J., and Siestrunck, R., "Etude des divers regimes d'écoulement dans l'elargissement brusque d'une veine supersonique", <u>Rev. Gen. Sci. Appl. Brussels</u>, II 4, 1955, pp. 229-237.

Faris, G. N., <u>Some Entrainment Properties of a Turbulent Axi-Symmetric Jet</u>, Research Report No. 39, Mississippi State University, Aerophysics Department, State College, Mississippi, January 1963.

Fasoli, U., "Theory of Vacuum Formation with Steam Jet Ejectors" (in Italian), <u>Termotecnia</u>, Volume 11, No. 9, September 1957, pp. 465-472.

Filimonov, A. G., "Gas Ejector" (Translation), <u>Auto Engr.</u> Volume 48, No. 7, July 1958, pp. 271-274.

Filleul, N. le S., <u>Basic Theory of the Supersonic Ejector Nozzle</u>, Report A.R.C. 25646 (P.A. 1004), Aeronautical Research Council, Britain, June 1963.

Finn, P. J., "Compressed-Air Venturi Ejectors and Blowers", <u>South Afr. Inst. Eng.</u>, Volume 44, 1943, pp. 70-94.

Fleming, W. A., <u>Internal Performance of Several Types of Jet-Exit Configurations for Supersonic Turbojet Aircraft</u>, RM E52K04, NACA, January 1953.

Fletcher, J. L., <u>Calculation of Airflow Through an Ejector-Operated Engine Cooling System for a Turbojet Powered Aircraft</u>, Report No. SM-14020, Douglas Aircraft Company, Incorporated, Santa Monica, California, May 1951.

Flinn, E. H., <u>Tests of Ejector Pump Configurations Designed for Use in the Ejector Flap Boundary Layer Control System</u>, WADC Technical Note 55-29, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, August 1957.

Fluegel, G., <u>The Design of Jet Pumps</u>, TM 982, NACA, July 1941.

Foa, J. V., <u>A New Method of Energy Exchange Between Flows and Some of Its Applications</u>, Technical Report TR AE 5500, Rensselaier Polytechnic Institute, Troy, New York, December 1955.

Foa, J. V., Energy Transfer Rate in Axial-Flow Crypto-Steady Pressure Exchange, Technical Report TR AE 6102, Rensselaer Polytechnic Institute, Troy, New York, February 1961.

Foa, J. V., Crypto-Steady Pressure Exchange, Technical Report TR AE 6202, Rensselaer Polytechnic Institute, Troy, New York, March 1962.

Foa, J. V., A Note on a Method of Energy Exchange, Technical Report TR AE 6208, Rensselaer Polytechnic Institute, Troy, New York, 1962.

Foa, J. V., "A Note on a Method of Energy Exchange", A.R.S. Journal, Volume 32, 1962, pp. 1396-1398.

Foa, J. V., "A Vaneless Turbopump", AIAA Journal, Volume 1, No. 2, February 1963, pp. 466-467.

Folsom, R. G., PPredicting Liquid Jet Pump Performance", Proceedings National Conference on Hydraulics, 1948.

Folsom, R. G., "Jet Pump with Liquid Drive", Chemical Engineering Progress, Volume 44, No. 765, 1948.

Fortini, A., Performance Investigation of a Nonpumping Rocket-Ejector System for Altitude Simulation, TN D-257, NASA, December 1959.

Forstall, W., Jr., and Shapiro, A. H., Momentum and Mass Transfer in Coaxial Gas Jets, Meteor Report No. 39, Massachusetts Institute of Technology, Department of Mechanical Engineering, July 1949.

Foster, R., Pre-test Report for Multiple Nozzle Jet Pump, Engineering Report No. 116, University of Wichita, School of Engineering, Wichita, Kansas, November 1953.

Fortini, A., Performance Investigation of a Nonpumping Rocket-Ejector System for Altitude Simulation, TN D-257, NASA, September 1959.

Fortini, A., Hendrix, C. D., and Huff, V. N., Experimental
Altitude Performance of JP-4 Fuel and Liquid-Oxygen Rocket
Engine with an Area Ratio of 48, Memo 5-14-59E, NASA,
1959.

Fournel, E., "Calcul approché sur les trompes à gaz",
La Rech. Aeron., No. 13, 1950, pp. 55-63.

Fox, N. L., Analytical Solutions for Gross Thrust Change
and Weight Flor Ratir Due to a Jet Ejector Pump, Report
No. SM-13881, Douglas Aircraft Company, Incorporated,
Santa Monica, California, December 1950.

Fox, N. L., The Pumping Characteristics of Long Mixing
Section Jet Pumps, Report No. SM-14385, Douglas Aircraft
Company, Incorporated, Santa Monica, California,
September 1952.

Freneau, P., et al, "Application of Steam-Jet Ejectors in
Houdry Fixed-Bed Catalytic Cracking Process", Trans.
A.S.M.E., Volume 69, 1947, p. 69.

Frenzl, O., Die Heisswasserstrahlpumpe zum Antrieb von
Windkanaelen, SNECMA Bericht 410-575-A, 1953.

Frenzl, O., "Uber die Entwicklung von intermittierend
arbeitenden Windkanaelen mit Strahlantrieben",
WGL Jahrbach, 1955.

Frenzl, O., "Der Heisswesserstrahlapparat", Luftfahrt,
Volume 4, February 1958, pp. 28-34.

Frenzl, O., "Eignung des Heisswasserstrahlapparates fuer
Triebwerkswindkanaele: beitrag zu den Problemen dieses
Strahlapparates", Luftfahrttechnik, Volume 8,
September 1962, pp. 224-233.

Freudenthal, "The Utilization of the Nozzle Action in
Ventilation of Ships" (in German), Schiffbau, July 1919.

Frost Engineering Development Corporation, Viscous Mixing of Two-Dimensional Jets with Particular Reference to Jets in Ground Proximity, TRECOM Technical Report 64-11 (Frost Report No. 197-4), U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, April 1964.

Gates, M. F., Evaluation of Annular Nozzle Ejector - Full Scale in Ground Effect, Report No. ARD 281, Hiller Aircraft Corporation, Palo Alto, California, November 1960.

Gates, M. F., and Cochran, C. L., Evaluation of Annular Nozzle Ejector, Report No. ARD-280, Hiller Aircraft Corporation, Palo Alto, California, November 1960.

Gates, M. F., and Cochran, C. L., Summary Report - Phase II Program. Annular Nozzle Ejector - Contract No. 2840(00), Report No. ARD-285, Hiller Aircraft Corporation, Palo Alto, California, February 1961.

Gates, M. F., and Fairbanks, J. W., Summary Report - Phase III Program. Annular Nozzle Ejector. Report No. ARD-300, Hiller Aircraft Corporation, Palo Alto, California, December 1961.

Geiger, F. W., The Application of One-Dimensional Analysis to Thrust Augmentation for Thermally Perfect but Calorically Imperfect Gases, Technical Note R-69, Brown Engineering Company, Huntsville, Alabama, September 1963.

German, R. C., and Bauer, R. C., Effects of Diffuser Length on the Performance of Ejectors without Induced Flow, AEDC-TN-61-89, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, August 1961.

German, R. C., and Panesci, J. H., Improved Methods for Determining Second-Thrust Diffuser Performance of Zero-Secondary-Flow Ejector Systems, AEDC-TR-65-124, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, July 1965.

Gertsma, L. W., and Yeager, R. A., Preliminary Investigation of Off-Design Performance of Divergent-Ejector-Type Rocket Nozzles, TM X-250, NASA, March 1960.

Goff, J. A., and Coogan, C. H., "Some Two-Dimensional Aspects of the Ejector Program", Journal of Applied Mechanics, Trans. ASME, Volume 64, December 1942, pp. A151-A154.

Gorton, G. C., Pumping and Drag Characteristics of an Aircraft Ejector at Subsonic and Supersonic Speeds, RM E54D06, NACA, June 1954.

Gosline, J. E., and O'Brien, M. P., "The Water Jet Pump", University of California Publications in Engineering, Volume 3, No. 3, 1934, pp. 167-190.

Gouse, S. W., Jr., and Leigh, J. H., Heat, Mass and Momentum Transfer Between a High Velocity Liquid Jet and a Concentric Gas Stream in an Axisymmetric Channel, Report No. 67, Joseph Kaye & Company, Cambridge, Massachusetts, January 1965.

Greathouse, W. K., Preliminary Investigation of Pumping and Thrust Characteristics of Full-Size Cooling-Air Ejectors at Several Exhaust-Gas Temperatures, RM E54A18, NACA, April 1954.

Greathouse, W. K., Performance Characteristics of Several Full-Scale Double-Shroud Ejector Configurations Over a Range of Primary Gas Temperature, RM E54F07, NACA, August 1954.

Greathouse, W. K., and Beale, W. T., Performance Characteristics of Several Divergent-Shroud Aircraft Ejectors, RM E55G21A, NACA, September 1955.

Greathouse, W. K., and Hollister, D. P., Preliminary Air-Flow and Thrust Calibrations of Several Conical Cooling-Air Ejectors with a Primary to Secondary Temperature Ratio of 1.0. I-Diameter Ratios of 1.21 and 1.10, RM E52E21, NACA, July 1952.

Greathouse, W. K., and Hollister, D. P., Preliminary Air-Flow and Thrust Calibrations of Several Conical Cooling-Air Ejectors with a Primary to Secondary Temperature Ratio of 1.0. II-Diameter Ratios of 1.06 and 1.40, RM E52F26, NACA, August 1952.

Greathouse, W. K., and Hollister, D. P., Air-Flow and
   Thrust Characteristics of Several Cylindrical Cooling-Air
   Ejectors with a Primary to Secondary Temperature Ratio of
   1.0, RM E52L24, NACA, March 1953.

Guienne, P., "Ejectors, or the Ejector Wing, Applied to
   V/STOL Aircraft", Journal of the American Helicopter
   Society, Volume 6, No. 3, July 1961, pp. 2-9.

Guienne, P., and Faure, M., "Applications des trompes au
   decollage vertical", V/STOL (Aircraft) Part I,
   Agardograph 89, September 1964, pp. 255-275.

Guman, W. J., Exploratory Experimental Study of a New Method
   of Energy Exchange Between Steady Flows, Technical Report
   TR AE 5811 (AFOSR TN-59-14), Rensselaer Polytechnic
   Institute, Troy, New York, May 1958.

Haak, W. H., and Vrátny, F., An Annular Jet Pump, Report
   TN 58-937, Air Force Office of Scientific Research,
   Washington, D. C., October 1958.

Hale, J. W., Auxiliary Ejector Effects on Rocket-Driven
   Diffuser Performance During Thrust Variation, AEDC-TDR-
   63-188, Arnold Engineering Development Center, Arnold
   Air Force Station, Tennessee, September 1963.

Hale, J. W., Comparison of Diffuser-Ejector Performance With
   Five Different Driving Fluids, AEDC-TDR-63-207, Arnold
   Air Force Station, Tennessee, October 1963.

Hale, J. W. Investigation of Two-Nozzle Cluster Diffuser-
   Ejector With and Without Ejected Mass, AEDC-TDR-63-130,
   Arnold Engineering Development Center, Arnold Air Force
   Station, Tennessee, November 1963.

Hale, J. W., Influence of Pertinent Parameters on Ejector-
   Diffuser Performance With and Without Ejected Mass,
   AEDC-TDR-64-134, Arnold Engineering Development Center,
   Arnold Air Force Station, Tennessee, July 1964.

Hansen, A. G., and Kinnavy, R., The Design of Water Jet Pumps. Part I - Experimental Determination of Optimum Design Parameters, Paper 65 WA/FE-31, ASME, November 1964.

Hansen, A. G., and Na, T. Y., Optimization of Jet Pump Systems, Paper 66-FE-4, ASME, April 1966.

Havill, C. D., and Wingrove, R. C., Flight Investigation of a Full-Scale Aircraft Ejector With Various Spacing Ratios and Correlation With Small-Scale Tests, RM A58D21, NACA, August 1958.

Hawthorne, E. P., and Zaporski, B., Exhaust Ejector Tests on a Merlin 46 Engine.

Hearth, D. P., and Connors, J. F., A Performance Analysis of Methods for Handling Excess Inlet Flow at Supersonic Speeds, TN 4270, NACA, May 1958.

Hearth, D. P., and Cubbison, R. W., Investigation at Supersonic and Subsonic Mach Numbers of Auxiliary Inlets Supplying Secondary Air Flow to Ejector Exhaust Nozzles, RM E55J12a, NACA, January 1956.

Hearth, D. P., Englert, G. W., and Kowalski, K. L., Matching of Auxiliary Inlets to Secondary-Air Requirements of Aircraft Ejector Exhaust Nozzles, RM E55D21, NACA, August 1955.

Hearth, D. P., and Valerino, A. S., Thrust and Pumping Characteristics of a Series of Ejector-Type Nozzles at Subsonic and Supersonic Flight Speeds, RM E54H19, NACA, November 1954.

Heinl, F., Untersuchungen an Dampfstrahlapparaten, VDI Forschungsheft 253, Germany, 1922.

Heinl, F., Untersuchungen an Dampfstrahlapparaten, VDI Forschungsheft 256, Germany.

Heinrich, A. M., Pre-test Report on the Performance Study of a Side-Inlet Jet-Pump With an Inboard Nozzle, Engineering Study No. 117, University of Wichita, School of Engineering, Wichita, Kansas, October 1953.

161

Heinrich, A. M., Performance Tests of a Side-Inlet, Steam-to-Air Jet Pump With an Inboard Nozzle, Engineering Report No. 131, University of Wichita, School of Engineering, Wichita, Kansas, February 1954.

Heinrich, A. M., Performance Tests of a Side Inlet, Steam-to-Air Jet Pump With an Inboard Nozzle and a Tapered Mixing Tube, Engineering Report No. 138, University of Wichita, School of Engineering, Wichita, Kansas, May 1954.

Heinrich, A. M., Summary of Performance Tests of Two Side Inlet, Steam-to-Air Jet Pumps, Engineering Report No. 146, University of Wichita, School of Engineering, Wichita, Kansas, June 1954.

Heiser, W. H., Thrust Augmentation, Paper 66-GT-116, ASME, April 1966.

Helmbold, H. B., Review of a Systemic Theoretical Investigation of Jet Pumps, Engineering Study No. 122, University of Wichita, School of Engineering, Wichita, Kansas, November 1953.

Helmbold, H. B., "Comparison of Mixing Pressures in Subsonic Jet Pumps", Journal of the Aeronautical Sciences, Volume 22, No. 6, June 1955, pp. 435-437.

Helmbold, H. B., Energy Transfer by Turbulent Mixing Under a Longitudinal Pressure Gradient, Engineering Study 182, University of Wichita, School of Engineering, Wichita, Kansas, August 1955.

Helmbold, H. B., Contributions to Jet Pump Theory, Report No. 294, The University of Wichita, Department of Engineering Research, Wichita, Kansas, September 1957.

Helmbold, H. B., Juessen, G., and Heinrich, A. M., An Experimental Comparison of Constant-Pressure and Constant-Diameter Jet Pumps, Engineering Report No. 147, University of Wichita, School of Engineering, Wichita, Kansas, July 1954.

162

Helmbold, H. B., and Wallace, R. E., Pre-test Report for a Systematic Investigation of Constant-Diameter and Constant-Pressure Jet Pumps, Engineering Study No. 121, University of Wichita, School of Engineering, Wichita, Kansas, November 1953.

Henderson, J. F., Performance of a Jet Pipe Ejector With Convergent Divergent Nozzle, I.D.R. 113, Bristol Aero-Engines Limited, Filton, Bristol, Britain, August 1956.

Hensley, R. V., Theoretical Analysis of the Performance of a Supersonic Ducted Rocket, RM E7I05, NACA, February 1948.

Higgins, D. G., An Assessment of the Suitability of Ejector Type Propelling Nozzles for Use on Supersonic Turbo-Jet Engines, Unpublished Ministry of Aviation Report, Britain, July 1956.

Hoeffer, K., Untersuchungen an Luftpumpen fuer Kondensatoren, VDI Forschungsheft 253.

Hoge, H. J., On the Theory of Mixing of Fluis Streams, Technical Report TR-2, Quartermaster Research & Engineering Center, Pioneer Research Division, Natick, Massachusetts, February 1959.

Hoge, H. J., "On the Theory of Mixing of Fluid Streams", Journal of the Aerospace Sciences, Volume 29, No. 1, January 1962, pp. 118-119.

Hoge, H. J., Eichacker, S. S., and Fiske, D. L., "Studies of Jet-Compression. I. Apparatus and Methods. Results With Air at Room Temperature", Journal of Basic Engineering, Trans. ASME, Series D, Volume 81, September 1959, pp. 426-432.

Hoge, H. J., and Segars, R. A., Further Studies of the Jet Compressor, Technical Report PR-9, Quartermaster Research and Engineering Center, Pioneer Research Division, Natick, Massachusetts, May 1963.

Hoge, H. J., Segars, R. A., "Choked Flow: A Generalization of the Concept and Some Experimental Data", AIAA Journal, December 1965, pp. 2177-2183.

Hohenemser, K. H., "Flow Induction by Rotary Jets", Journal of Aircraft, Volume 3, No. 1, January-February 1966, pp. 18-24.

Hohenemser, K. H., "Preliminary Analysis of a New Type of Thrust Augmentation", Proceedings 4th U. S. National Congress of Applied Mechanics, ASME, 1962, pp. 1291-1299.

Hohenemser, K. H., and Porter, J. L., "Contribution to the Theory of Rotary Jet Flow Induction", Journal of Aircraft, Volume 3, No. 4, July-August 1966, pp. 339-346.

Holder, D. W., The High-Speed Laboratory of the Aerodynamics Division, NPL., R & M 2560, Aeronautical Research Council, London, Britain, 1954.

Hollister, D. P., and Greathouse, W. K., Performance of Double-Shroud Ejector Configuration With Primary Pressure Ratios From 1.0 to 10, RM E52K17, NACA, February 1953.

Holmes, M., An Investigation Into Mixing Between By-Pass Air and Turbine Exhaust Gases. Part I - Experimental Facilities and Procedure, N.G.T.E. Report No. R.261, National Gas Turbine Establishment, Pyestock, Hants, Britain, March 1964.

Holmes, M., An Investigation Into Mixing Between By-Pass Air and Turbine Exhaust Gases. Part II - Experimental Results at a By-Pass Ratio of 0.65, N.G.T.E. Report No. R.262, National Gas Turbine Establishment, Pyestock, Hants, Britain, March 1964.

Holmes, M., An Investigation Into Mixing Between By-Pass Air and Turbine Exhaust Gas. Part III - Experimental Results at By-Pass Ratio of 1.3, N.G.T.E. Report No. R.263, National Gas Turbine Establishment, Pyestock, Hants, Britain, July 1964.

Holmes, M., An Investigation Into Mixing Between By-Pass Air and Turbine Exhaust Gases. Part IV - An Analysis of the Pressure Losses Due to Mixing, N.G.T.E. Report No. R.277, National Gas Turbine Establishment, Pyestock, Hants, Britain, December 1965.

164

Holton, W. C., "Effect of Molecular Weight of Entrained Fluid on the Performance of Steam-Jet Ejectors", ASME Trans., 1951, p. 905.

Holton, W. C., and Schultz, E. J., "Effect of Temperature of Entrained Fluid on the Performance of Steam-Jet Ejectors", ASME Trans., 1951, p. 911.

Hood, J. H., Analysis of Aircraft Ejector Cooling Performance, Report R-447-A, United Aircraft Corporation, Research Division, East Hartford, Connecticut, October 1945.

Hood, J. H., Compressed Air Tests of Single and Multiple Nozzle Ejectors, Report R-450, United Aircraft Corporation, Research Division, East Hartford, Connecticut.

Hood, J. H., Compressed Air Tests of Single and Multiple Nozzle Ejectors With Diffusers, Report R-450 A, United Aircraft Corporation, Research Division, East Hartford, Connecticut, June 1944.

Howell, A. R., Note on the Theory of Simple Thrust Augmentation for Jet Propulsion, RAE Note E.3886, Royal Aircraft Establishment, Farnborough, Britain, August 1941.

Howell, R. R., Experimental Operating Performance of a Single-Stage Annular Air Ejector, TN D-23, NASA, October 1959.

Huddleston, S. C., Wilsted, H. D., and Ellis, C. W., Performance of Several Air Ejectors With Conical Mixing Sections and Small Secondary Flow Rates, RM E8D23, NACA, July 1948.

Hudson, Saunders, and Broughton, Thrust From Ejector Exhausts, Part III, RAE Report No. Eng. 414, ARC 7843, Aeronautical Research Council, London, Britain, 1944.

Hughes, D. P., and Tadman, K. G., Performance Characteristics of a Series of Divergent Shroud Ejectors, AV Roe P/Power/95, January 1957.

165

Hunczak, H. R., and Rousso, M. D., <u>Starting and Operating Limits of Two Supersonic Wind Tunnels Utilizing Auxiliary Air Injection Downstream of the Test Section</u>, TN 3662, NACA, September 1954.

Hunter, K., <u>An Experimental Jet Engine Ejector Tunnel</u>, Report No. ME-167, National Research Council of Canada, Ottawa, Canada, December 1948.

Huntley, S. C., and Yanowitz, H., <u>Pumping and Thrust Characteristics of Several Divergent Cooling-Air Ejectors and Comparison of Performance With Conical and Cylindrical Ejectors</u>, RM E53T13, NACA, January 1954.

Hussmann, A. W., <u>Eductors for Hydraulic Systems Applied to Closed-Circuit Lubrication Systems</u>, WADC Technical Report 53-131, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, September 1952.

Hussmann, A. W., Eductor Design Manual, The Pennsylvania State College, Department of Engineering Research, State College, Pennsylvania, May 1953.

Hussmann, A. W., <u>Ventilation Eductors in Gas Turbine Exhaust Stacks</u>, The Pennsylvania State College, Department of Engineering Research, State College, Pennsylvania, May 1953.

Hussmann, A. W., <u>Eductors for Hydraulic Systems</u>, Bulletin No. 64, The Pennsylvania State College, Department of Engineering Research, State College, Pennsylvania, February 1955.

Irving, F. G., "A Note on the Theory of the Constant Area Mixing of Compressible Flows as Applied to High-Speed Wind Tunnel Design", Aeronautical Quarterly, Volume 4, 1953, p. 105.

Jackson, D. H., "Selection and Use of Ejectors", <u>Chemical Engineering Process</u>, No. 44, 1948, pp. 347-352.

Jacobs, E. N., and Shoemaker, J. M., <u>Tests on Thrust Augmentors for Jet Propulsion</u>, TN 431, NACA, 1932.

166

Johannesen, N. H., Ejector Theory and Experiments, A.T.S.
No. 1, Trans. Danish Acad. Tech. Copenhagen, Denmark, 1951.

Johnson, J. K., Jr., Shumpert, P. K., and Sutton, J. F.,
Steady Flow Ejector Research Program, ER-5332, Lockheed-
Georgia Company, Marietta, Georgia, September 1961.

Jones, W. L., Price H. G., Jr., and Lorenzo, C. G.,
Experimental Study of Zero-Flow Ejectors Using Gaseous
Nitrogen, TN D-203, NASA, March 1960.

Jung, R., "Calculation and Application of Ejectors" (in
German), Forsch. Geb. Ing.-Wes. (B) 26, 1960, p. 32;
VDI Forschungsheft, 479, 1960, p. 33.

Kalmykov, I. I., "The Calculation of a Gas Ejector" (in
Russian), Aviats. Tekh. No. 2, Izv. Vyssh. Uchebn.
Zavedenii, 1958, pp. 93-103.

Kalustian, P., "Analysis of the Ejector Cycle", Refrigeration
Engineering, Volume 28, No. 188, 1934.

Kaplunov, M. P., "Apparatus for the Testing of Ejector
Models" (in Russian), In-ta Inzh.-d. Transp., No. 21,
Trudi, Rostovsk, 1958, pp. 251-268.

Kastner, L. J., and Spooner, J. R., "An Investigation of
the Performance and Design of the Air Ejector Employing
Low-Pressure Air as the Driving Fluid", Proceedings of the
Institution of Mechanical Engineers, Volume 162, 1950,
pp. 149-166.

Kastner, L. J., and McGarry, J. B., "Mass Flow and Mixing
Process in Low-Velocity Air Ejectors", Engineer, Volume 210,
No. 5453, July 1950, pp. 190-192.

Katto, Y., "On the Ejector Used for Locomotives" (in Japanese),
Japan Res. Inst. Sci. Technol. Volume 4, January-February
1950, pp. 44-49.

Kaye, J., and Rivas, M. A., Experimental and Analytical Study
of Two-Component Two-Phase Flow in Ejector With Conden-
sation, Paper 57-HT-35, ASME, August 1957.

Keenan, J. H., and Neumann, E. P., "A Simple Air Ejector",
ASME Trans., Volume 64, 1942, pp. A75-A84.

Keenan, J. H., Neumann, E. P., and Lustwerk, F., "An
Investigation of Ejector Design by Analysis and Experiment",
Journal of Applied Mechanics, Trans. ASME, Volume 17, No. 3,
September 1950, pp. 299-309.

Kennedy, E. D., The Ejector Flow Process, Thesis, University
of Minnesota, Minneapolis, Minnesota, June 1955.

Kennedy, E. D., "Mixing of Compressible Fluids", Journal of
Applied Mechanics, Trans. ASME, Volume 28, No. 3,
September 1961.

Kennedy, E. D., "Comment on the Theory of Mixing of Fluid
Mechanics", Journal of the Aerospace Sciences, Volume 29,
No. 5, May 1962, pp. 609-610.

Kerr, S. L., "The Moody Ejector Turbine", Trans. ASMF,
Volume 43, No. 1828, 1921, pp. 1201-1217.

Khristianovich, S. A., "About Ejector Calculation" (in
Russian), Coll. Industrial Aerodynamics, No. 3, 1944.

Kiefer, M. D., An Analysis of the Properties of Two-
Dimensional Incompressible Fluid Flow in the Mixing
Chamber of a Constant Area Ejector, Thesis (M.S.), United
States Naval Postgraduate School, Monterey, California,
1963.

Kiselev, B. M., Calculation of One-Dimensional Gas Flows
(Translation), Technical Report No. F-TS-1209-1A
(GDAM A9-T-27), Air Materiel Command, Wright-Patterson
Air Force Base, Ohio, January 1949.

Kispert, E. G., The Complete Air Ejector, Thesis (M.S.),
Massachusetts Institute of Technology, Cambridge,
Massachusetts, 1943.

Kivnick, G., Studies on a Non-Isothermal Jet Discharging Into
a Duct, Technical Report CML-1, University of Illinois,
Engineering Experimental Station, Urbana, Illinois, 1951.

Klann, J., and Huff, R. G., Characteristics of Five Ejector Configurations at Free-Stream Mach Numbers from 0 to 2.0, TM X-23, NASA, Auguat 1959.

Klein, H., The Thrust and Drag Penalties on a Jet Engine Installation Due to Cooling Flow, Report No. SM-13862, Douglas Aircraft Company, Incorporated, Santa Monica, California, November 1950.

Klingensmith, Mixing of Compressible Fluid Streams, Report No. R-12006-02, United Aircraft Corporation, February 1948.

Knoernschild, E. M., The Design and the Performance Calculation of Ejectors and Aspirators, Air Force Technical Report No. 6673, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, April 1951.

Knowles, A. E., and Holder, D. W., The Efficiency of High-Speed Wind Tunnels of the Induction Type, R. & M. No. 2448, Aeronautical Research Council, London, Britain, 1954.

Knox, R. M., A Study of Optimized Constant Pressure Jet Pumps, Report No. 5827A, The Marquardt Corporation, Van Nuys, California, December 1960 (Revised March 1962).

Knox, R. M., "The Optimized Ejector-Nozzle Thrust Augmentor", Journal of the Aerospace Sciences, Volume 29, No. 4, April 1962, pp. 470-471.

Koch, W., Untersuchungen eines ziveristufigen Dampfstrahl Apparates mit Zwischen- und Nachkondensation, Dissertation, Technische Hochschole, Berlin, 1928.

Kochendorfer, F. D., Effect of Properties of Primary Fluid on Performance of Cylindrical Shroud Ejectors, RM 53L24a, NACA, March 1954.

Kochendorfer, F. D., Notes on Performance of Aircraft Ejector Nozzles at High Secondary Flows, RM E54F17a, NACA, August 1954.

Kochendorfer, F. D., and Rousso, M. D., Performance
    Characteristics of Aircraft Cooling Ejectors Having Short
    Cylindrical Shrouds, RM E51E01, NACA, May 1951.

Korst, H. H., Addy, A. L., and Chow, W. L., Installed
    Performance of Air Augmented Nozzles Based on Analytical
    Determination of Internal Ejector Characteristics,
    CR-64301, NASA, 1965.

Korst, H. H., and Chow, W. L., Compressible Non-Isoenergetic
    Two-Dimensional Turublent Jet Mixing at Constant Pressure,
    M. E. Technical Note 392-4, University of Illinois,
    Urbana, Illinois, January 1959.

Korst, H. H., Page, R. H., and Childs, M. E., Compressible
    Two-Dimensional Jet Mixing at Constant Pressure,
    M. E. Technical Note 392-1, University of Illinois,
    Urbana, Illinois, April 1954.

Korst, H. H., Page, R. H., and Childs, M. E., Compressible
    Two-Dimensional Jet Mixing at Constant Pressure,
    M. E. Technical Note 392-3, University of Illinois,
    Urbana, Illinois, April 1955.

Kort, L., "Raketen mit Strahlapparat", Zeischrift fuer
    Flugtechnik und Motorluftschriftfahrt, Jahrg. 23, Nr. 16,
    August 1932, pp. 483-486.

Kravath, "The Venturi Ejector for Handling Air - Part I",
    Heating and Ventilating, Volume 37, No. 6, 1940, p. 17,
    and Volume 37, No. 8, 1940, p. 46.

Kroll, A. E., "The Design of Jet Pumps", Chemical Engineering
    Progress, Volume 43, No. 2, February 1947, p. 21.

Krzywoblocki, M. Z., Jets, Technical Memo No. 1576,
    U. S. Naval Ordnance Test Station, Inyokern, China Lake,
    California, September 1953.

Krzywoblocki, M. Z. V., Jets - Review of Literature, Project
    Squid Technical Report No. PR-68-P, Princeton University,
    James Forrestal Research Center, Princeton, New Jersey,
    November 1956.

Kuethe, A. M., "Investigation of th~ Turbulent Mixing
Regions Formed by Jets", Jounral of Applied Mechanics,
Volume 2, No. 3, September 1935, pp. A87-A95.

Kumm, E. L., Friedman, J., and Kanarek, I. A., Ejector
Performance, Report AL-793, North American Aviation,
Incorporated, Los Angeles, California, November 1948.

Laidlaw, W. R., Ejector Theory and Its Application to
Induction Type Wind Tunnels, Report No. MA-232, National
Research Council of Canada, Ottawa, Canada, August 1950.

Lamb, N. A., "Steam Ejectors for High Vacua", World Power,
Volume 17, October 1925, p. 200.

Ledgett, L. A., Mixing of Fluid Streams, Preprinted Paper,
ASME Aeronautics and Hydraulics Division, Summer Meeting,
Berkeley, California, June 1934.

Lee, J. D., The Induction of Flow by an Injection Nozzle,
Research Bulletin 128, Purdue University Engineering
Experimental Station, Lafayette, Indiana, 1955.

Lee, J. D., "The Induction of Flow by an Injection Nozzle",
Proceedings, Fourth Midwestern Conference on Fluid
Mechanics, 1955, pp. 355-370.

Lee, J. G., Progress Report on Augmented Jet Propulsion,
Report R-48, United Aircraft Corporation, Research
Division, East Hartford, Connecticut, October 1940.

Le Grives, E., "Amélioration des performances d'extraction
d'un éjecteur supersonique par préchauffage du flux moteur",
La Rech. Aero., No. 78, September-October 1960, pp. 23-29.

Le Grives, E., Fabri, J., and Paulon, J., Diagrammes pour le
calcul des éjecteurs a flux moteur supersonique, Note
Technique No. 35, Office National d'Etudes et de
Recherches Aeronautiques, Paris, France.

Le Grives, E., Fabri, J., and Paulon, J., Diagrammes pour le calcul des éjecteurs supersoniques, Note Technique No. 36, Office National d'Etudes et de Recherches Aeronautiques, Paris, France, 1956.

Le Grives, E., and Paulon, J., "Sur une propriete simple d'adaptation optimale des éjecteurs supersoniques", La Rech. Aero., No. 50, March-April 1956, pp. 27-30.

Levy, J., The Mixing of Vapor and Liquid Jets, Report No. 1344, U. S. Navy, Office of Naval Research, Washington, D. C., October 1957.

Lewis, W. G. E., and Cook, D., Experiments on Air Ejectors for Ram-Jet Altitude Testing, NGTE Memorandum No. M102, National Gas Turbine Establishment, Pyestock, Hants, Britain, January 1951.

Lewis, W. G. E., and Drabble, J. S., Ejector Experiments, NGTE Report No. R151, National Gas Turbine Establishment, Pyestock, Hants, Britain, February 1954.

Lilley, G. M., and Holder, D. W., Experiments on an Induction Type High Speed Wind Tunnel Driven by Low Pressure Steam, Report 24, College of Aeronautics, March 1949.

Lindsey, W. F., and Chew, W. L., Development Performance of Two Small Tunnels Capable of Intermittent Operation at Mach Numbers Between 0.4 and 4.0, TN 2189, NACA, September 1950.

Lindsey, W. F., Choking of a Subsonic Induction Tunnel by the Flow From an Induction Nozzle, TN 2730, NACA, July 1952.

Linkovskiy, G. B., "Calculation of a Noncylindrical Ejector", Mixing of Concentric High Velocity Air Streams. Compilation of Abstracts (Translation), ATD Report P-65-33, Library of Congress, Aerospace Technology Division, May 1965, pp. 10-12.

172

Little, B. H., Jr., and Cubbage, J. M., Jr., Effects of
Combining Auxiliary Bleed With Ejector Pumping on the
Power Requirements and Test-Section Flow of an 8-Inch
by 8-Inch Slotted Tunnel, RM L55E25, NACA, July 1955.

Lockwood, R. M., Pulsejet Ejectors, Thesis (M.E.), Oregon
State College, Corvallis, Oregon, June 1953.

Lockwood, R. M., Investigation of the Process of Energy
Transfer From an Intermittent Jet to an Ambient Fluid:
Summary Report for the Period 1 December 1958 to
30 June 1959, Report No. ARD-238, Hiller Aircraft
Corporation, Palo Alto, California, June 1959.

Lockwood, R. M., Interim Technical Report on Investigation
of the Progress of Energy Transfer From an Intermittent
Jet to Secondary Fluid in an Ejector-Type Thrust
Augmenter, Report No. ARD-275, Hiller Aircraft Corporation,
Palo Alto, California, September 1960.

Lockwood, R. M., Investigation of the Mechanism of Energy
Transfer From an Intermittent Jet to the Secondary Fluid
in an Ejector Type Thrust Augmenter, Report ARD-282,
Hiller Aircraft Corporation, Palo Alto, California,
November 1960.

Lockwood, R. M., Interim Summary Report of Investigation of
the Process of Energy Transfer From an Intermittent Jet
to Secondary Fluid in an Ejector-Type Thrust Augmenter,
Report No. ARD-286, Hiller Aircraft Corporation, Palo
Alto, California, March 1961.

Lockwood, R. M., and Patterson, W. G., Pulse Reaction Lift-
Propulsion System Development Program - Interim Report,
Report No. ARD-301, Hiller Aircraft Corporation, Palo
Alton, California, December 1961.

Lockwood, R. M., and Patterson, W. G., Interim Summary
Report Covering the Period From 1 April 1961 to 30 June
1962 on Investigation of the Process of Energy Transfer
From an Intermittent Jet to Secondary Fluid in an Ejector-
Type Thrust Augmenter, Report No. ARD-305, Hiller Aircraft
Corporation, Palo Alto, California, June 1962.

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Lockwood, R. M., and Sander, H. W., <u>Investigation of the Process of Energy Transfer From an Intermittent Jet to Secondary Fluid in an Ejector-Type Thrust Augmenter. Interim Summary Report Covering the Period From 30 October 1962 to 31 March 1964</u>, Report No. APR-64-4, Hiller Aircraft Company, Palo Alto, California, March 1964.

Lockwood, R. M., and Sargent, E. R., <u>Direct Lift Propulsion Research</u>, Hiller Helicopters Engineering Report No. 533.3, Hiller Aircraft Corporation, Palo Alto, California.

Lockwood, R. M., Sargent, E. R., and Beckett, J. E., <u>Thrust Augmented Intermittent Jet Lift-Propulsion System "Pulse-Reacter"</u> - Final Report, Report No. ARD-256, Hiller Aircraft Corporation, Palo Alto, California, February 1960.

London, A. L., and Pucci, P. F., <u>Exhaust-Stack Ejector for Sweeper Boat Gas Turbine Installations</u>, Stanford University, Stanford, California, August 1952.

London, A. L., and Pucci, P. F., <u>Exhaust-Stack Ejectors for Marine Gas Turbine Installations</u>, Technical Report No. 26, Stanford University, Stanford, California, July 1955.

Lorell, J., <u>Static Ducted Rocket</u>, Report No. 3-8, Jet Propulsion Laboratory, GALCIT, California Institute of Technology, Pasadena, California, August 1946.

Lorell, J., <u>Additional Theoretical Results on the Performance of the Subsonic Ducted Rocket</u>, Report No. 3-11, Jet Propulsion Laboratory, GALCIT, California Institute of Technology, Pasadena, California, October 1946.

Loth, J. L., <u>Theoretical Optimization of Staged Ejecter Systems, Part I</u>, AEDC-TR 66-2, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, March 1966.

Love, E. S., and O'Donnell, R. M., <u>Investigation at Supersonic Speeds of External-Drag Characteristics of a Short Ejector</u>, RM L55D28, NACA, June 1955.

174

Lukasiewicz, J., Note on Exhaust Actuated Air Ejector Design, Technical Note No. Eng. 352, Royal Aircraft Establishment, Farnborough, Britain, June 1945.

Lutz, O., Gas Dynamic Mixing Processes. Thrust Increase by Jet Mixing (Translation), MOA TIL/T. 5349, Ministry of Aviation, London, Britain, January 1964.

Lutz, O., and Riester, E., "Uber die Auslegung zweistufiger Heisswasserejektoren", Z. fuer Flugwissenschaften, Volume 7, Number 12, 1959, pp. 350-355.

Lutz, O., and Riester, E., "Ergbnisse der Durchsatzmessungen am Heisswasserejektor der DFL in Braunschweig", Z. fuer Flugwissenschaften, Volume 11, 1963, pp. 79-85.

Lutz, O., Riester, E., and Lindemann, R., Uber die Aufheizung von Speichern zum Betrieb von Heisswassere jektoren, Bericht Nr. 154, Inst. fuer Strahltriebwerke, Germany, 1961.

Lynch, G. R., and Carman, C. T., An Investigation of the Performance of a Hot-Gas Jet Pump With and Without Induced Flow, Report AEDC-TDR-64-234, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, December 1964.

Manganiello, E. J., A Preliminary Investigation of Exhaust-Gas Ejectors for Ground Cooling, WR E-210 (ACR), NACA, July 1942.

Manganiello, E. J., and Bogatsky, D., An Experimental Investigation of Rectangular Exhaust Gas Ejectors Applicable for Engine Cooling, TR 818, NACA, 1954.

Marquardt, R. E., A Theoretical and Experimental Investigation of Exhaust Ejectors for Cooling at Low Speeds, ACR 3G05, NACA, July 1943.

Marquardt, R. E., Tests of an Annular Ejector System for Cooling Aircraft Engines, ACR 3J27, NACA, October 1943.

Marquardt, R. E., **A Study of Cooling and Exhaust Disposal in Submerged Engine Installations**, ACR 3J28, NACA, October 1943.

Martin Company, **Recirculation Principle for Ground Effect Machine Two-Dimensional Tests**, TCREC Technical Report 62-66, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, June 1962.

Martin Company, **Recirculation Principle for Ground Effect Machines, Three-Dimensional Wind Tunnel Tests**, TCREC Technical Report 62-74, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, July 1962.

Martin Company, **Recirculation Principle for Ground Effect Machines, Man-Carrying Test Vehicle and Component Testing**, TCREC Technical Report 62-99, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, February 1963.

Martin Company, **Recirculation Principle for Ground Effect Machines Man-Carrying Test Vehicles. Preliminary Flight Test Results**, TCREC Technical Report 62-100, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, December 1962.

Martin Company, **Recirculation Principle for Ground Effect Machines: Investigation of Improvements by Major Modifications to MCTV**, TRECOM Technical Report 63-27, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, July 1963.

Martin Company, **Recirculation Principle for Ground Effect Machine: Preliminary Design of a Research Vehicle**, TRECOM Technical Report 64-27, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, August 1964.

Matsunaga, S., "On the Mach Number at the Diffuser Throat of an Ejector According to the Hydraulic Analogy", **J.A.S.**, Volume 24, No. 12, December 1957, pp. 918-919.

McCarter, B., Hughes, D., and Allen L., <u>The Optimization of Ejector Geometry for the C105 Incorporating the Iroquois</u> Engine, AV Roe Rept. P/Power/97, Feburary 1957.

McClintock, F. A., <u>High Velocity Tests of Ejectors</u>, Report R-403, United Aircraft Corporation, Research Division, East Hartford, Connecticut, December 1943.

McClintock, F. A., <u>Theoretical Calculation of Steady-Flow Ejector Performance</u>, Report R-447, United Aircraft Corporation, Research Division, East Hartford, Connecticut, May 1944.

McClintock, F. A., and Hood, J. H., "Aircraft Ejector Performance", <u>Journal of the Aeronautical Sciences,</u> Volume 13, No. 11, November 1946, pp. 559-568.

McCloy, R. W., <u>Preliminary Report to Mathematical Analysis of Injector Jet</u>, Report No. 9-1, University of Illinois, Aeronautical Engineering Department, Urbana, Illinois, September 1946.

McCloy, R. W., <u>The Air Intake for the Ejector Jet</u>, Report No. 9-3, University of Illinois, Aeronautical Engineering Department, Urbana, Illinois, February 1947.

McCloy, R. W., <u>The Actuating Nozzle for the Ejector Jet</u>, Report No. 9-5, University of Illinois, Aeronautical Engineering Department, Urbana, Illinois, July 1947.

McCloy, R. W., <u>The Ejector Ram Jet, Final Report</u>, University of Illinois, Urbana, Illinois, May 1954.

McCloy, R. W., and Zabinsky, J. M., <u>Performance of the Ejector Jet</u>, Report No. 9-8, University of Illinois, Department of Aeronautical Engineering, Urbana, Illinois, May 1950.

McElroy, G. E., <u>Effect of Size and Shape of Pipe and of Adjacent Walls on Velocity and Entrainment Ratio, Part 2,</u> Rep. Inv. 3730, U.S.D.I., Bureau of Mines, 1943.

McElroy, G. E., <u>Design of Injectors for Low-Pressure Air Flow</u>, Technical Paper 678, Bureau of Mines, 1945.

177

McFarland, A. R., Investigation of an Air Ejector ump for High Altitude Sampling Systems, AT(11-1)-40, TID-16073, General Mills Incorporated, May 1962.

McJones, R. W., Sain, J. A., and Flores, J. R., Generalized Performance of Cylindrical and Conical Aircraf Ejectors, Engineering Report No. LB-25320, Douglas Ai craft Company, Incorporated, Long Beach, California, December 1950.

Medici, M., The Design of Jet Ejectors", Engineering Digest, Volume 14, February 1953, p. 51.

Meerbaum, S., and Shein, E., The General Case of Entrainment Mixing and Compression of Gases in a Straight Mixing Tube, Report No. SPD 88, The M. W. Kellogg Company, Jersey City, New Jersey, May 1947.

Meise, N. R., Preliminary Report on Testing Ejectors With an Obstruction Located in the Center of the Diffuser, Report M-3070-1, United Aircraft Corporation, Research Division, East Hartford, Connecticut, September 1946.

Meise, N. R., Additions to Testing Program on Ejectors, Report P-3070-2, United Aircraft Corporation, Research Division, East Hartford, Connecticut, December 1946.

Meise, N. R., Comparative Tests of Several Ejector Arrangements, Report No. R-3070-3, United Aircraft Corporation, Research Division, East Hartford, Connecticut, November 1947.

Melot, H. F., French Patents 522163 (1919); 523427 (1920); 571863 (1922).

Mendrala, J., Evaluation of a Mixed-Flow Augmenter/Aerodynamic-Boattail-Nozzle System, NATTS-ATL-102, Naval Air Turbine Test Station, Aeronautical Turbine Laboratory, Trenton, New Jersey, August 1965.

Meyer, E., Zur Theorie der Dampfstrahl-Luftpumpe, Dissertation, Technische Hochschule Berlin, Berlin, Germany, 1920.

Mickey, F. E., The Determination of the Pumping and Thrust
Characteristics of Axially Symmetric Jet Ejectors With
Various Mixing Section Configurations, Report No. ES
15237, Douglas El Segundo Aircraft Corporation,
El Segundo, California, 1949.

Mickey, F. E., A Study of the Characteristics of Turbine
Engine Side Exit Jet Ejector Configurations, Report No.
ES 21301, Douglas Aircraft Company, Incorporated,
El Segundo, California, June 1949.

Mickey, F. E., An Investigation of the Pumping and Thrust
Characteristics of a Jet Ejector Operating at High Tempera-
ture and Pressure, Report No. ES 21468, Douglas Aircraft
Company, Incorporated, El Segundo, California, June 1949.

Mihaloew, J. R., and Stofan, A. J., Internal-Performance
Evaluation of a Two-Position Divergent Shroud Ejector,
TN D-762, NASA, January 1961.

Mihaloew, J. R., Internal-Performance Evaluation of Two
Fixed-Divergent-Shroud Ejectors, TN D-763, NASA,
January 1961.

Mikhail, S., "Mixing of Coaxial Streams Inside a Closed
Conduit", Journal of Mechanical Engineering Science,
Volume 2, No. 1, March 1960, pp. 59-68.

Miller, G. P., Efficiencies and Entrainment Ratios of Air
Jet Pumps, Thesis (M.S.), Case School of Applied Science,
Cleveland, Ohio, 1940.

Miller, K. D., Jr., Flow in Ejectors Driven by Supersonic
Jets, Project Squid Technical Memorandum No. Pr-3,
Princeton University, Princeton, New Jersey, May 1948.

Mitchell, H., Jr., An Optical Study of Ejector Performance,
Thesis (M.S.), GAE 56-3, Air Force Institute of Technology,
Wright-Patterson Air Force Base, Ohio, August 1956.

Mitchell, J. W., Design Parameters for Subsonic Air-Ejectors,
Technical Report No. 40, Stanford University, Department
of Mechanical Engineering, Stanford, California,
December 1958.

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Montague, H. B., _Report on Analytical Study of Ejectors_, Report No. 1360, The Martin Company, Orlando, Florida, December 1960.

Moore, J. L., Finamore, O. B., and Wilder, J. G., _Preliminary Study of a Supersonic Induction Type Wind Tunnel for Cornell Aeronautical Laboratory_, CAL Report No. DD-420-A-8, Cornell Aeronautical Laboratory, Buffalo, New York, September 1947.

Moos, H. R., _Analytical and Experimental Study of Low Pressure Air Ejector Pumps_, Paper for S.A.E. Meeting December 14, 1953.

Morghen, K., and Rothe, K., "Boundary Layer Suction With the Aid of Exhaust Jet" (in German), _Z. Flugweiss_, Volume 3, No. 11, November 1955, pp. 371-373.

Morrisson, R., _Jet Ejectors and Augmentation_, Report R-74 (Revised), United Aircraft Corporation, Research Division, East Hartford, Connecticut, October 1941.

Morrisson, R., _Jet Ejectors and Augmentation_, ACR, NACA, September 1942.

Moss, E. T., "Mixing of Liquids by Injector Action", _Journal of Imperial College Chemical Engineering Society_, Volume 3, No. 64, 1947.

Mueller, F., "Dampfstrahlapparat als Luftpumpe fuer Kondensationsanlagen", _Schiffbau_, Volume 24, 1923, p. 486.

Mullins, J. W., _The Effect of Boundary Layer Energization on the Thrust of an Ejector_, Thesis (M.S.), GA/ME/60-10, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, August 1960.

Namoradze, A. G., "An Experimental Universal Ejector" (in Georgian), Shromebi No. 3 (60), Sakartoelos Politeknikuri Inst., 1958, pp. 86-92.

Nelson, J. R., Investigation of the Mixing Region Between
the Primary and Secondary Streams of a Two-Dimensional
Supersonic Air-Ejector System, Thesis (M.S.), GAM
65B/ME/65-6, Air Force Institute of Technology, Wright-
Patterson Air Force Base, Ohio, June 1965.

Neumann, E. P., Air Jet Ejectors, Thesis (M.S.),
Massachusetts Institute of Technology, Cambridge,
Massachusetts, May 1941.

Nicholson, R., and Lowry, R. B., XV-4A VTOL Research
Aircraft Program Summary Report, USAAVLABS Technical
Report 66-45, U. S. Army Aviation Materiel Laboratories,
Fort Eustis, Virginia, May 1966.

North, W. J., Transonic Drag of Several Jet-Noise
Suppressors, TN 4269, NACA, April 1958.

North, W. J., and Coles, W. D., Effect of Exhaust-Nozzle
Ejectors on Turbojet Noise Generation, TN 3573, NACA,
October 1955.

Norton, H. T., Jr., Cassetti, M. D., and Mercer, C. E.,
Transonic Off-Design Performance of a Fixed Divergent
Ejector Designed for a Mach Number of 2.0, TM X-165,
NASA, December 1959.

O'Donnell, R. M., and McDearmon, R. W., Experimental
Investigation of Effects of Primary Jet Flow and Secondary
Flow Through a Zero-Length Ejector on Base and Boattail
Pressures of a Body of Revolution at Free-Stream Mach
Numbers of 1.62, 1.93, and 2.41, RM L54I22, NACA,
December 1954.

Pai, S. I., Part II of Final Report on Phase I of the Study
of Air Exchange Problems in Supersonic Tunnels, Report No.
AD-570-A-6, Cornell Aeronautical Laboratory, Incorporated,
Buffalo, New York, January 1949.

Palmieri, F. L., A Theoretical Comparison of Three Unders¸ ₐr
Thrust Augmentation Systems, Report No. TR AE 6301,
Rensselaer Polytechnic Institute, Troy, New York,
February 1963.

Panesci, J. H., and German, R. C., *An Analysis of Second-Throat Diffuser Performance for Zero-Secondary-Flow Ejector Systems*, AEDC-TDR-63-249, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, December 1963.

Papin, V. M., "Experimental Investigation of Phenomena Occurring in the Mixing Chamber of a Water Jet Pump" (in Russian), DAN USSR, Volume 84, No. 5, 1952.

Paris, F. G., et al, *Exhaust Gas Ejector Tubes in Association With Explosion Engines of Internal Combustion Engines*, U. S. Patent No. 2,864,235, December 1958.

Patston, D., *Construction and Testing of Small Central Nozzle Ejector Operating Off the High Pressure Air Supply*, Thesis, Sydney University, Department of Aeronautical Engineering, Sydney, Australia, 1957.

Payne, P. R., "The Development of Ducted Rocket Power Units for Models", *Proceeding of the First Model Aeronautics, The Royal Aeronautical Society*, London, Britain, September 1954.

Payne, P. R., *An Introduction to Ground Effect Machine Recirculation Theory*, Report No. 142-2, Frost Engineering Development Corporation, Englewood, Colorado, January 1963.

Payne, P. R., *Viscous Mixing Phenomena With Particular Reference to Thrust Augmentors*, Paper No. 64-798, American Institute of Aeronautics and Astronautics, October 1964.

Payne, P. R., *Steady-State Thrust Augmentors and Jet Pumps*, USAAVLABS Technical Report 66-18, United States Army Aviation Materiel Laboratories, Fort Eustis, Virginia, March 1966.

Payne, P. R., and Anthony, A., *Tests of Three Axisymmetric Model Eductors*, Report No. 57, Peter R. Payne Associates, Rockville, Maryland, November 1964.

Payne, P. R., and Anthony, A., *An Exploratory Investigation of Mixing Losses in a Two-Dimensional Propulsive Jet*, Working Paper No. 25-27, Payne Incorporated, Rockville, Maryland, June 1965.

Pearson, H., Holliday, J. B., and Smith, S. F., "A Theory of the Cylindrical Ejector Supersonic Propeller Nozzle", *Journal of the Royal Aeronautical Society*, Volume 62, No. 574, October 1958, pp. 746-751.

Perini, R. L., Walker, R. E., and Dugger, G. L., *Preliminary Study of Air Augmentation of Rocket Thrust*, Report No. TG 545, John Hopkins University, Applied Physics Laboratory, Silver Spring, Maryland, January 1964.

Peters, C. E., and Wehofer, S., *Constant Area Mixing of Nonisoenergetic Coaxial Compressible Streams*, AEDC-TR-61-18, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, January 1962.

Peters, C. E., and Wehofer, S., *A General Investigation of Two-Stream Supersonic Diffusers*, AEDC-TDR-62-22, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, March 1962.

Peters, C. E., and Wehofer, S., *Theoretical Performance of Air-Driven Ejectors for Pumping Rocket Exhaust Gases*, Report AEDC-TDR-62-134, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, June 1962.

Petrie, S. L., *Investigation of Co-Axial Air Injection in a Hypersonic Wind Tunnel*, ARL-62-394, Aeronautical Research Laboratories, Wright-Patterson Air Force Base, Ohio, August 1962.

Pfleiderer, C., *Der Strahlpumpenantrieb mit Zumischung von Umgebungsfluessigkeit zum treibstrahl*, ZWB, FB 812.

Phillips, W. H., and Rauscher, M., "Propulsive Effects of Radiator and Exhaust Ducting", *Journal of Aeronautical Sciences*, February 1941.

Pinkel, B., Turner, L. R., and Voss, F., Design of Nozzles for the Individual Cylinder Exhaust Jet Propulsion System, ACR, NACA, April 1941.

Pinkerton, D. W., Thrust Augmentation of a Supersonic Jet, Thesis (M.S.), Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, 1959.

Pool, H. L., and Charyk, J. V., Theoretical and Experimental Investigations of the Mixing of a Supersonic Stream With an Induced Secondary Stream as Applied to Ducted Propulsive Devices, Project Squid, Report No. 25, Princeton University, Princeton, New Jersey, 1950.

Portnov, I. G., Stationary Working Conditions of a Supersonic Gas Ejector (Translation), FTD-TT-65-153/1+2, Air Force Systems Command, Foreign Tech. Division, Wright-Patterson Air Force Base, Ohio, June 1965.

Portnov, I. G., "Theory and Calculation of Operating Steady-State Regime of a Supersonic Gas Ejector" (in Russian), Trudi Vses. Nauki In-ta Prirodn. Gazov., No. 2 (10), 1958, pp. 130-162.

Portnov, I. G., "The Stability of the Steady-State Working of a Supersonic Gas Ejector" (in Russian), Trudi Vses. Nauki In-ta Prirodn. Gazov., No. 5 (13), 1959, pp. 251-266.

Portnov, I. G., and Zotov, G. A., Consecutive Operation of Gas Ejectors Under Steady-State Conditions (Translation), FTD-TT-63-184, Air Force Systems Command, Foreign Technical Division, Wright-Patterson Air Force Base, Ohio, April 1963.

Pucci, P. J., Simple Ejector Design Parameters, Thesis (Ph.D.), Stanford University, Stanford, California, September 1954.

Quigg, C. G., The Design and Testing of a Two-Stage Ejector for Simulated High Altitude Gas Turbine Combuster Testing, ARL Note ME 249, Aeronautical Research Laboratories, Australia, March 1957.

Rabeneck, G. L., Shumpert, P. K., and Sutton, J. F.,
Steady Flow Ejector Research Program, Report ER-4708
Lockheed Aircraft Corporation, Georgia Division,
Marietta, Georgia, December 1960.

Rasof, B., Theoretical Subsonic Performance of a Ducted
Rocket, Report No. 3-3, Jet Propulsion Laboratory, GALCIT,
California Institute of Technology, Pasadena, California,
August 1945.

Rateau, A., "Nouvelle théorie des trompes. Experiences
verificatrices", Revue de Mecanique, 2eme semetre, Paris,
1900, pp. 264-314.

Regnier, C. F. E., Notes on Two American Re; orts on the
Improvement of Cooling by Exhaust Gas Driven Air Ejectors,
Technical Note No. Aero 1379, Royal Aircraft Establishment,
Farnborough, Britain, February 1944.

Reid, E. G., Annular-Jet Ejectors, TN 1949, NACA,
September 1947.

Reid, J., The Effect of a Cylindrical Shroud on the
Performance of a Stationary Convergent Nozzle, R. & M.
No. 3320, Aeronautical Research Council, London, Britain,
January 1962.

Reshotko, E., Performance Characteristics of a Double-
Cylindrical Shroud Ejector Nozzle, RM E53H28, NACA,
November 1953.

Rhodes, R. P., Evaluation of Hot-Water-Driven Diffuser
Ejectors, AEDC-TN-59-127, Arnold Engineering Development
Center, Arnold Air Force Station, Tennessee, November 1959.

Richards, W. G., and Osborne, W. C., "The Very Low Pressure
Air Ejector", Instn. Heat. and Ventilat. Engrs., Volume 27,
September 1959, pp. 172-179.

Ridder, W. C., and Summers, C. R., Theoretical Analysis of
the Heated Jet Pump and Design of a Test Facility, Thesis
(M.S.), United States Naval Postgraduate School,
Monterey, California, May 1966.

Rolls, L. S., and Havill, C. D., An Evaluation of Two Cooling-Air Ejectors in Flight at Transonic Speeds, RM A54A05, NACA, March 1954.

Romanienko, P. N., "Contribution à la theorie d l'éjection et au calcu des éjecteurs" (in Russian), Sect. de Sci. Tech. No. 6, Anal. de L'Academie des Sciences de l'URSS, June 1953, pp. 837-855.

Rose, R. F., Report on Progress on the Investigation of the Use of Hot Gas Ejectors for Boundary Layer Control, Progress Report Nos. 39, 40 and 41, University of Minnesota, Institute of Technology, Department of Aeronautical Engineering, Rosemount Aeronautical Laboratories, Minneapolis, Minnesota, 1957.

Rotta, G., "Ejektorpumpen mit extrem hohen Durchsalzver-haeltnis", Forschung Gebiete Ing. Ausg., A., No. 4, 1957, pp. 157-167.

Roy, M., "Sur la théorie du mélangeur isobar d'une trompe à gaz parfaits", CR Acad. Sci., Volume 217, 1943, p. 189.

Roy, M., "Sur la théorie approachée des trompes à liquides", Assoc. Tech. Maritime et Aeronautique, Volume 44, 1945.

Roy, M., "Sur la théorie sommaire des trompes à gaz", Bulletin due Groupement Francais pour le Developpement de Recherches Aeronautiques, No. 2, 1946, pp. 21-32.

Roy, M., Tuyeres trompes fusées et projectiles: problèmes divers de dynamique des fluides aux grandes vitesses, PST 203, Min. de l'Air, Paris, France, 1947.

Roy, M., Problemes divers de mécanique des fluides concernant la propulsion par réaction, PST 203, Min. de l'Air, Paris, France, 1947.

Roy, M., Theoretical Investigations on the Efficiency and the Conditions for the Realization of Jet Engines, TM 1259, NACA, June 1950.

Royds, R., and Johnson, E., "Fundamental Principles of the Steam Ejector", Proceedings of the Institution of Mechanical Engineers, Volume 145, 1941, pp. 193-209.

Rumckel, J. F., Preliminary Transonic Performance Results for Solid and Slotted Turbojet Nacelle Afterbodies Incorporating Fixed Divergent Jet Nozzles Designed for Supersonic Operation, Memo 10-24-58L, NASA, December 1958.

Saenger, E., Air Admixture to Exhaust Jets, TM 1357, NACA, July 1953.

Samuels, J. C., and Yanowitz, H., Analysis of Several Methods of Pumping Cooling Air for Turbo-Jet Engine Afterburners, RM E52K26, NACA, February 1953.

Sanders, J. C., "Analysis of Ejector-Thrust by Integration of Surface Pressures", NACA Conference on Cooling-Air Ejectors, Misc. A. C. 1948, pp. 25-42.

Sanders, J. C., and Brightwell, V. L., Analysis of Ejector Thrust by Integration of Calculated Surface Pressures, TN 1958, NACA, October 1949.

Sandover, J. (Editor), The Jet-Pump as an Alternative Means of Providing Lift in Air-Cushion Vehicles, Report No. 20, Norman K. Walker Associates, Incorporated, Bethesda, Maryland, August 1965.

Sargent, E. R., Theoretical Performance of a Static Thrust Augmenter, Report No. R-150 Curtiss-Wright Corporation, Airplane Division, St. Louis, Missouri, July 1944.

Sargent, E. R., Theoretical Performance of a Dynamic Thrust Augmenter, Report No. R-158, Curtiss-Wright Corporation, Airplane Division, St. Louis, Missouri, December 1944.

Sargent, E. R., and Lockwood, R. M., Direct Lift Propulsion Research, Report No. 5333, Hiller Aircraft Corporation, Palo Alto, California, November 1955.

187

Schafer, E., and Michely, W., Ergebnisse von Pruefstandsversuchen mit Heisswassermodellraketen, Stuttgart Forschungs-institute fuer Physik der Strahlantriebe Mit 11, 1957.

Schlag, A., A propos due calcul des éjecteurs, Centre Belge d'Etude et de Documentation des Eaux No. 41 III, 1958.

Schwarzler, K., "Untersuchungen an Heisswasserrakten zum Start von Flugzeugen", Z. Flugweiss, Volume 6, No. 1, 1958, pp. 1-8.

Schmeer, J. W., Salters, L. B., Jr., and Cassetti, M. D., Transonic Performance Characteristics of Several Jet Noise Suppressors, TN D-388, NASA, July 1960.

Schneitter, Diffuser Studies With Single and Two-Phase Flows, Report No. TM 62-1, Purdue University, Jet Propulsion Center, Lafayette, Indiana, April 1962.

Schubauer, G. B., Jet Propulsion With Special Reference to Thrust Augmentors, TN 442, NACA, January 1933.

Scott, A. W., and Jamieson, J., "Nozzle Effects in an Air Ejector", J. Royal Technical College of Glasgow, Volume 3, 1935, pp. 627-635.

Scupp, F., "Regelbare Mehrfach-Strahlsauger", VDI Zeit, Volume 101, No. 34, December 1959, pp. 1630-1635.

Seddon, J., and Dyke, M., Ejectors and Mixing of Streams, Bibliography 6, AGARD, Paris, November 1964.

Segars, R. A., and Hoge, H. J., Some Effects of Jet-Compressor Geometry on Efficiency: Compression-Ratio Curves With Two Maxima, Technical Report PR-10, U. S. Army Natick Laboratories, Natick, Massachusetts, June 1964.

Sheldon, J. A., and Hunczak, H. R., An Analytical and
   Experimental Evaluation of a Two-Stage Annular Air
   Ejector for High-Energy Wind Tunnels, TN D-1215, NASA,
   June 1962.

Shillito, T. B., and Koffel, W. K., Experimental Investiga-
   tion of Ejector-Nozzle Metal Temperatures, RM E56K20,
   NACA, February 1957.

Shue, J. W., and Stauffer, J. K., Research on Coaxial Jet
   Air Mixing. Final Report-Phase I, CONVAIR Report,
   June 1960.

Shumpert, P. K., Equations for Prediction of Ejector
   Performance With Loss of Pressure in Secondary Flow at
   Entrance to Ejector, Unpublished Report, Lockheed Aircraft
   Corporation, Georgia Division, Marietta, Georgia,
   April 1958.

Shumpert, P. K., Theoretical Ejector Performance-Compressible
   Flow Analysis, Unpublished Report, Lockheed-Georgia
   Company, Marietta, Georgia, January 1960.

Shumpert, P. K., Progress Report for Steady Flow Research
   Program, Report ER-4671, Lockheed Aircraft Corporation,
   Georgia Division, November 1960.

Shumpert, P. K., The Hummingbird XV-4A Ejector Lift Improve-
   ment Program, Report ER-7697, Lockheed-Georgia Company,
   Marietta, Georgia, January 1965.

Simonson, A. J., and Schmeer, J. W., Static Thrust
   Augmentation of a Rocket-Ejector System With a Heated
   Supersonic Primary Jet, TN D-1261, NASA, May 1962.

Sirieix, M., Contribution to the Study of Supersonic
   Ejectors (Translation), Library Translation No. 8,
   Aircraft Research Assoc. Ltd., Bedford, Britain, May 1963.

Slatter, B. H., and Bailey, W., Note on Simple Thrust
   Augmentation for Jet Propulsion Units, Technical Note No.
   Eng. 121, Royal Aircraft Establishment, Farnborough,
   Britain, March 1943.

Smith, F. H., Jr., <u>Capability and Cost Study for Component and Model Test Facility, Phase I, Supplement 1, Analytical Systems With Interstate Cooling</u>, AEDC-TR-65-139, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, August 1965.

Smith, F. H., Jr., <u>Capability and Cost Study for Component and Model Test Facility, Phase I, Supplement 2, Design of Exhauster System for Selected Cases</u>, AEDC-TR-65-140, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, July 1965.

Smith, F. H., Jr., <u>Design and Performance of Staged Steam Ejectors With Interstage Condensers</u>, AEDC-TR-65-257, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, March 1966.

Smith, R. A., "Theory and Design of Simple Ejectors", <u>Conference on Some Aspects of Fluid Flow, Inst. Phys. at Leamington Spa.</u>, 1940.

Smith, R. A., "Theory and Design of Simple Ejectors", <u>Some Aspects of Fluid Flow</u>, Edward Arnold and Company, London, 1951, pp. 229-241.

Socha, W., <u>Analysis of the Performance of Aircraft Ejectors</u>, Technical Note Ac 103, English Electric Company, Britain, May 1957.

Speaker, W. V., "Wind Tunnel Investigation of a 1/16 Scale Model of the Proposed Annular Steam Ejector for the Trisonic Four-Foot Wind Tunnel", <u>Results of Independent Research and Development Studies by the Douglas Aerophysics Lab, Staff in Fluid Mechanics and Simulation Techniques Fiscal Year 1962</u>. Report SM-41379, Section 6, Douglas Aircraft Company, Incorporated, Santa Monica, California, January 1963.

Spencer, D. A., and Bennett, A. S., <u>Model Tests on an Effuser Induction Scheme for Operating a Transonic Wind Tunnel</u>, Technical Note No. Aero 2514, Royal Aircraft Establishment, Farnborough, Britain, June 1951.

Spiegel, J. M., Holstetter, R. U., and Kuehn, D. M.,
  Applications of Auxiliary Air Injectors to Supersonic
  Wind Tunnels, RM A53I01, NACA, November 1953.

Spiegelberg, C. H., Summary Report - Phase I Program.
  Annular Nozzle Ejector - Contract No. 2840(00), Report No.
  ARD-243, Hiller Aircraft Corporation, Palo Alto,
  California, November 1959.

Spiegelberg, C. H., and Gates, M. F., Annular Ejector Test
  Program - Summary for Contract Nonr 2840(99), Report No.
  ARD-267, Hiller Aircraft Corporation, Palo Alto,
  California, June 1960.

Squire, H. B., and Trouncer, J., Round Jets in a General
  Stream, Reports and Memoranda 1974, Aeronautical Research
  Committee, London, Britain, January 1944.

Stechkin, B. S., Methodology for the Calculation and
  Measurements Relative to the Mixing of Gases (Translation),
  FTD-TT-62-448/1 2, Air Force Systems Command, Foreign
  Technology Division, Wright-Patterson Air Force Base, Ohio,
  August 1965.

Stephanovskii, B. S., Small Scale Ejector Models (Translation),
  FTD-TT-62-448/1 2, Air Force Systems Command, Foreign
  Technology Division, Wright-Patterson Air Force Base, Ohio,
  July 1962.

Sterbentz, W. H., Cylindrical Ejector Performance With Fully
  Entrained Secondary Flow, TIS Report No. 59FPD387,
  General Electric Company, Component Engineering Division,
  Danville, California, April 1959.

Stitt, L. E., and Valerino, A. S., Effect of Free-Stream
  Mach Number on Gross-Force and Pumping Characteristics of
  Several Ejectors, RM E54K23a, NACA, March 1955.

Stofan, A., J., Effects of Nozzle-Shroud Misalignment on
  Performance of a Fixed-Shroud Divergent Ejector,
  TM X-97, NASA, March 1960.

191

Stofan, A. J., and Mihaloew, J. R., Performance of a
Variable Divergent-Shroud Ejector Nozzle Designed for
Flight Mach Number up to 3.0, TM X-255, NASA,
January 1961.

Storkebaum, C., Die Anwendung des Ejektors bei V/STOL
Flugzeugen und dessen Auslegung, DFL-Bericht Nr. 234,
Deutsche Forschungsanstalt fuer Luft- und Raumfahrt E. V.,
Braunschweig, Germany, 1964.

Storkebaum, C., Die Anwendung des Ejektors bei V/STOL
Flugzeugen und dessen Auslegung -2. Teilbericht,
DLRFB 64-25, Deutsche Luft- und Raumfahrt
Forschungsanstalt, E. V., Braunschweig, Germany,
August 1964.

Storkebaum, C., Die Anwendung des Ejektors bei V/STOL
Flugzeugen und dessen Auslegung -3. Teilbericht,
DLR FB 65-25, Deutsche Luft- und Raumfahrt
Forschungsanstalt E. V., Braunschweig, Germany, April 1965.

Stand, G. E., A Study of a Supersonic Ejector Mixing Chamber,
Thesis (M.S.), GAM 65B/ME/65-8, Air Force Institute of
Technology, Wright-Patterson Air Force Base, Ohio,
June 1965.

Surendraiah, M., and Rao, D. M., Performance Characteristics
of Two-Dimensional Center Jet Ejector, Report No. TN AE
18-63, National Aeronautical Laboratory, Bangalore, India,
July 1963.

Swihart, J. M., and Mercer, C. E., Investigation at
Transonic Speeds of a Fixed Divergent Ejector Installed
in a Single-Engine Fighter Model, RM L57L10a, NACA,
March 1958.

Swihart, J. M., Mercer, C. E., and Norton H. T., Jr.,
Effect of Afterbody-Ejector Configuration on the
Performance at Transonic Speeds of a Pylon-Supported
Nacelle Model Having a Hot-Jet Exhaust, TN D-1399, NASA,
October 1962.

Szczeniowski, B., Theory of the Jet Syphon, TN 3385,
NACA, May 1955.

Szczeniowski, B., "La Théorie de l'éjecteur sous pression
constant pour augmenter la poussée", L'Ingenieur, No. 163,
August 1955.

Szlenkier, T. K., and Shumpert, P. K., Experimental
Investigation of Single Stage Ejectors Designed for High
Thrust Augmentation, Report ER-3449, Lockheed Aircraft
Corporation, Georgia Division, Marietta, Georgia,
March 1959.

Taylor, D., Barton, D. L., and Simmons, M., An Investigation
of Cylindrical Ejectors Equipped With Truncated Conical
Inlets, Phase II, AEDC-TN-60-224, Arnold Engineering
Development Center, Arnold Air Force Station, Tennessee,
March 1961.

Third, A. D., "The Air Ejector", J. Royal Technical College
of Glasgow, Volume 1, No. 4, December 1927, pp. 84-103.

Timbie, T. R., Additional Data on the Use of Ejectors at
the Jet Nozzle to Improve Cooling of Gas Turbine
Installations, Bulletin No. DF 81425, General Electric
Company, Aircraft Gas Turbine Engineering Division,
Schenectady, New York, September 1945.

Towle, H. C., and Judd, F. V. H., "Ejectors for Cooling a
Turbojet Installation", Aeronautical Engineering Review,
Volume 10, No. 9, September 1951, pp. 20-24.

Traksel, J., Subsonic Air-Air Ejectors and Jet Thrust
Augmentors, Report No. 14898, Lockheed-California Company,
Burbank, California, January 1963.

Trout, A. M., Papell, S. S., and Povolny, J. H., Internal
Performance of Several Divergent-Shroud Ejector Nozzles
With High Divergence Angles, RM E57F13, NACA,
October 1957.

Tsien, H. S. (Editor), Jet Propulsion, Air Technical Service
Command, 1946, pp. 394-398.

Turner, R., and White, M. D., Flight Tests of NACA Jet-Propulsion Exhaust Stacks on the Supermarine Spitfire Airplane, WR L-680, NACA, December 1942.

Tuve, G. L., Priester, G. B., and Wright, D. K., "Entrainment and Jet Pump Action of Air Streams", Heating, Piping and Air Conditioning, Volume 13, No. 11, 1941, p. 708.

Uebelhack, H., Supersonic Air-Air Ejectors With Second Throat Diffuser, Technical Note 28, von Karman Institute for Fluid Mechanics, Rhode-Saint-Genesee, Belgium, August 1965.

Uryukov, B. A., "Theory of Differential Ejector", Journal of Applied Mechanics and Technical Physics (Selection of Articles), Translation FTD-MT-64-61, Air Force Systems Command, Foreign Technology Division, Wright-Patterson Air Force Base, Ohio, February 1965, pp. 61-71.

Valerino, A. S., and Stitt, L. E., Effect on Ejector Performance of Varying Diameter Ratio by Simulated Iris Flaps, RM E55B25, NACA, April 1955.

van der Lingen, T. W., "A Jet Pump Design Theory", Journal of Basic Engineering Trans. ASME, Volume 82, December 1960, pp. 947-960.

Vasilyev, Y. N., Great-Pressure-Drop Gas Ejector With Additional Nozzle (Translation), FTD-TT-64-1198, Air Force Systems Command, Foreign Technology Division, Wright-Patterson Air Force Base, Ohio, April 1965.

Viktorin, K., Investigation of Turbulent Mixing Processes, TM 1096, NACA, 1941.

Vil'der, S. I., "A Simplified Method of Calculating Steamjet Ejecter Vacuum Pumps", International Chemical Engineering, Volume 4, No. 1, 1964, p. 88.

Vogel, R., A Contribution to the Design of Ejectors, Translation 4354, Safety in Mine Res. Estab.

von Kármán, "Theoretical Remarks on Thrust Augmentation", *Reissner Anniversary Volume*, J. W. Edwards, Ann Arbor, Michigan, 1949, pp. 461-468.

von Kármán, T., Tsien, H. S., and Canright, R., *A Study of the Possibility of Using the Ejector Action of the Jet as a Source of Power for Driving Propellant Pump*, Air Corps Jet Propulsion Research, Calcit Project No. 1, California Institute of Technology, Pasadena, California, July 1943.

Wagner, F., and McCune, C. J., *A Progress Report on Jet Pump Research*, Engineering Report No. 085, University of Wichita, School of Engineering, Wichita, Kansas, October 1952.

Wagner, G., *A Contribution to the Development of Jet Pumps* (translation), Air Force Translation F-TS-3559-RE, September 1947.

Wallner, L. E., and Jansen, E. T., *Full-Scale Investigation of Cooling Shroud and Ejector Nozzle for a Turbojet Engine-Afterburner Installation*, RM E51J04, NACA, December 1951.

Wan, C. A., *A Study of Jet Ejector Phenomena*, Research Report No. 57, Mississippi State University Aerophysics Department, State College, Mississippi, November 1964.

Wanner, M., *Introduction a etude des trompes thermo-propulsives*, PST 190, Min. de l'Air, Paris, France, 1944.

Watson, F. R. B., "The Production of a Vacuum in an Air Tank by Means of a Steam Jet", *Engineering*, Volume 1351, 1933; also, *Proceedings of the Inst. of Mechanical Engineers*, Volume 124, 1933, pp. 231-265.

Weatherston, R., "Mixing of Any Number of Streams in a Duct of Constant Cross-Sectional Area", *Journal of the Aeronautical Sciences*, Volume 16, No. 11, November 1949, pp. 697-698.

Weber, H. E., "Ejector-Nozzle Flow and Thrust", *Journal of Basic Engineering, Trans. ASME*, Volume 82, No. 1, March 1960, pp. 120-130.

Weber, H. E., "Ejector Nozzle Flow and Thrust for Choked Flow", *Journal of Basic Engineering Trans. ASME*, Volume 83, No. 3, September 1961, pp. 471-477.

Weeks, W. S., "The Air Injecter for Auxiliary Ventilation Underground", *Engineering and Mining Journal*, Volume 138, No. 4, April 1937, p. 196.

Weinig, F., *Analysis of the Thrust Augmentation Nozzle for High Velocity Drag Reduction*, Technical Report No. F-TR-2212-ND, Air Materiel Command, Wright-Patterson Air Force Base, Ohio, May 1948.

Wells, W. G., *Theoretical and Experimental Investigation of a High Performance Jet Pump Utilizing Boundary Layer Control*, Research Report No. 30, Mississippi State University, Aerophysics Department, State College, Mississippi, June 1960.

Weydanz, W., "Die Vorgaenge in Strahlapparaten", *Kaelte-Industrie*, Beihefte zur Zeitzchrift fuer die Gesamite, Reihe 2, Heft 8, 1938.

Wilder, J. C., *A Theoretical and Experimental Investigation of Jet Augmentation*, Report No. BC-357-A-1, Curtiss-Wright Corporation.

Wilder, J. G., Jr., *Part I of Final Report on Phase I of the Study of Air Exchange Problems in Supersonic Tunnels*, Report No. AD-570-A-5, Cornell Aeronautical Laboratory, Buffalo, New York, January 1949.

Wilder, J. G., Jr., and Hindersinn, K., *Final Report on Phase II of the Study of Air Exchange Problems in Supersonic Wind Tunnels*, Report No. AD-570-A-7, Cornell Aeronautical Laboratory, Buffalo, New York, January 1953.

196

Wilsted, H. D., "Correlation of Model and Jet Engine
Ejecter Data", NACA Conference on Cooling-Air Ejectors,
Misc. A. G. 1948, pp. 10-18.

Wilsted, H. D., "Thrust Characteristics of an Ejector
Pump", NACA Conference on the Turbojet Engine for
Supersonic Aircraft Propulsion, A Compilation of the
Papers Presented, July 1951.

Wilsted, H. D., Huddleston, S. C., and Ellis, C. W.,
Effect of Temperature on Performance of Several Ejector
Configurations, RM E9E16, NACA, June 1949.

Winter, H., On the Use of Jet Drives for Wind Tunnels of
High Velocity, Translation No. 219, David Taylor Model
Basin, Washington, D. C., April 1947.

Witte, J. H., Mixing Shocks and Their Influence on the
Design of Liquid Gas Ejectors, Delft University Waltman,
The Netherlands, 1962.

Wood, R. D., Theoretical Ejector Performance and Comparison
With Experimental Results, Technical Report 54-556,
Wright Air Development Center, Wright-Patterson Air Force
Base, Ohio, August 1954.

Wood, M. N., and Howard J. B. W., The Development of
Injector Units for Jet-Lift Engine Simulation on Low-
Speed-Tunnel Models, Technical Report No. 65020, Royal
Aircraft Establishment, Farnborough, Britain,
February 1965.

Work, L. T., and Haedrich, V. W., "Performance of Ejectors
as a Function of the Molecular Weights of Vapors",
Industrial and Engineering Chemistry, Volume 31, No. 4,
April 1939, pp. 464-477.

Work, L. T., and Miller, A., "Factor C in the Performance
of Ejectors as a Function of Molecular Weights of
Vapors", Industrial and Engineering Chemistry, Volume 32,
1940, pp. 1241-1243.

Yakovlevskiy, O. V., The Mixing of Jets in a Channel With Variable Cross Section (Translation), FTD-TT-62-1571/1+2+4, Air Force Systems Command, Foreign Technology Division, Wright-Patterson Air Force Base, Ohio, January 1963.

Yakovlevskiy, O. V., "An Hypothesis on the Universality of Ejection Properties of Turbulent Gas Jets and Its Application" (Translation), News of the Academy of Sciences of the USSR (Selected Articles), Translation FTD-TT-63-222/1+1+2+4, Air Force Systems Command, Foreign Technology Division, March 1963, pp. 1-30.

Yakovlevskiy, O. V., Principle of Turbulent Mixing of Coaxial Flows in a Channel of Constant Cross Section (Translation), FTD-TT-63-1139/1+2+4, Foreign Technology Division, Wright-Patterson Air Force Base, Ohio, March 1964.

Yakovlevskiy, O. V., Mixing of Jets in a Channel of Variable Cross Section (Translation), Report No. TIL/T.5410, Ministry of Aviation, London, July 1964.

Yakovlevskiy, O. V., Laws of Turbulent Mixing of Coaxial Flows in a Channel of Constant Cross Section (Translation), Report No. T.L/T. 5411, Ministry of Aviation, London, July 1964.

Yakovlevskiy, O. V., and Baker, I., Hypothesis of Universal Ejection Properties of Turbulent Jets of Gas and Its Applications (Translation) RSOC-108, Redstone Scientific Information Center, Redstone Arsenal, Alabama, December 1963.

Yeager, R. A., Investigation of an Ejector-Type Nozzle for Rocket Application, TM X-251, NASA, March 1960.

Yen, K. T., and Iskay, V., On the Induction and Mixing in a Duct, TR AE 5601, Rensselaer Polytechnic Institute, Troy, New York, December 1956.

Yen, S. M., Armstrong, G. L., and McCloy, R. W., Mixing, Diffusion and Pressure Recovery in the Ejector Jet, Report 9-6, University of Illinois, Aeronautical Engineering Department, Urbana, Illinois, 1948.

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13. ABSTRACT

Presented in this investigation is a theoretical analysis of the thrust augmentation characteristics of jet ejectors. The analysis includes the effects of flow compressibility, major flow losses, and forward speed. Numerical results are presented in the form of nomographs for a wide range of practical operating conditions. These computations were performed with the aid of an IBM digital computer. The charts can be used to predict the jet ejector performance and as such represent an effective analytical tool for preliminary design purposes. The numerical results are used to determine the effects of the more important aerodynamic, thermodynamic, and geometric parameters on jet ejector thrust augmentation. A correlation of these results with the available experimental data is also made.

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